Università Politecnica delle Marche
Scuola di Dottorato di Ricerca in Scienze dell'Ingegneria
Corso di Dottorato in Ingegneria Industriale
Curriculum in Ingegneria Meccanica

VIRTUAL ECO-DESIGN: An eco-design approach driven by virtual prototyping and knowledge management to support the development of sustainable products

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XVII edition - new series

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“Rem tene, Verba sequentur”
Cato the Elder

“To the engineer falls the job of clothing the bare bones of science with life, comfort, and hope.”
H.Hoover

Acknowledgements

This thesis is part of the research work co-financed by Electrolux S.p.A. and Università Politecnica delle Marche.

My first thanks go to these Institutions and Company for having given me the opportunity to accomplish this experience. I wish to express my most gratitude to my advisor, Prof. Michele Germani, for his guidance through the Ph.D. years and for having involved me in several interesting research projects.

A big gratitude goes to Prof. Daniel Brissaud for having welcomed me in his research group at G-Scop laboratory in Grenoble. This experience has allowed me to growth in know-how and capabilities both on technical and personal side. In particular, I wish to thank Maud Rio and Damien Evrard for giving me their professionality and their passion for the research world.

Thanks go to my colleagues of DT&M group, whose numerous suggestions have contributed to considerable improvements in this thesis. In particular I would to thank Marta Rossi and Claudio Favi, whose professionality and knowledge have inspired me during these years.

Thanks to my sweet colleague Florence Betmont whose friendship has made less sad French and foggy days in Grenoble.

Last but not least, my family: Mamma, Papà ….my strength and my roots. Thank you. What else!

My sister, Chiara who have shared with me every day of little achievements and sacrifices of this experience since the early days of my course of study. You are the “Piece of My Heart”.

Caterina e Pietro, without whose support I wouldn’t be the person I am today. Michele, Emanuele, Costy the new generations of “Russo Family”. Andrea, my little “polpetta” who have given me joy and smiles and tenderness with her new glance on the world.

Thanks to my friends, Luana my 24/7 moral support friend, your friendship is a great treasure for me, Rino her partner in crime and Roberto, who I don’t remember how long I’ve known.

Finally, Alberto, a special thanks for you. Thank you for always being with me when I need you. Thank you for having support me in things that I did not think I could do alone. I hope our dreams come true close together.

Abstract

In recent years, the environmental problem has acquired growing importance in industry and companies' sustainability policy. In the industrial field, eco-design represents an approach to integrate the environmental aspects in the product development process. The research and the academic world have answered with the development of a high number of methods and tools, which try to support companies in the design of ecological products.

Despite the great number of existing tools and methods, the developed solutions are usually too far from the industrial needs and companies still face some difficulties to implement eco-design in their design process. These difficulties can be identified as technical limitations of methodologies, complexity of tools, involvements of specialized personnel, hard integration within the product development process, etc.

This research work aims at providing a methodological framework called Virtual Eco-Design (VE) aiming to support designers and engineers in development of energy related sustainable products.

The methodology guides the designers through the design process combining existing design tools and environmental requirements. The VE approach has been conceived to assist engineers in ecological design choices thanks the consultation of an eco-knowledge collected in a structured database that integrates contents related to eco-design and virtual prototyping: eco-design guidelines and regulations for the evaluation of product, product information, virtual prototyping studies of different configurations, performances studies, etc.

The methodology is characterized by two complementary aspects: creation and sharing of the environmental knowledge through the database to facilitate the problem solving through the design/re-design process and the acquiring of competences on the sustainability issues. The proposal has been implemented in industrial cases applied to design/re-design of household appliances to experimentally measure the results of the choices made with the VE approach.

The experimentation results demonstrate the validity of the proposal and shows that 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. The VE approach provides a tangible support in the decision-making process evaluating the effect of the design choices since the early phase of the product development.

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Chapter 1.

Introduction

1.1 The Environmental Issue in Industry

Nowadays, the environmental issues are acquiring more and more importance related to the industrial products, in particular to household appliances. Household appliances represent 25% of European energy consumption and the EU 20-20-20 Energy and Climate Package aims to improve the energy efficiency in all sectors by 2020 with a 20% reduction in consumption. Household appliance contribute to these values and consequently require particular attention as far as sustainability is concerned. The EU Commission (EC) has been regulating the requirements regarding the energy consumption with the EU Eco-design Directive (Directive 2009/125/EC) and the EU Energy Labelling Directive (Directive 2010/30/EU). These regulations are the milestones for the energy efficiency and the general reduction of energy consumptions and present strict requirements for energy -related products.

It is well known that early design decisions, during Conceptual and Embodiment Design phases, influence the total product. During these phases, decisions about costs, materials, layouts, costs are taken but often the environmental dimension is neglected, and the evaluation of performances is difficult. The sustainability of a product is largely defined during the early design stage, but due to high level of uncertainty regarding embodiments at early design phase, new methodologies and tool are necessary to support designers and the pursuit of more energy-efficient products introduces an additional cost and time in the design of every product.

Actually, affirmed design methods and software tools support designers in choices in the cited design stages and robust tools provide designers with environmental evaluation. Several eco-design tools and procedures have been developed but they are often too far from industrial context and a practical day-by-day application in company engineering departments. Currently, there are no commercial software tool or methodologies that can concurrently support engineer in the product configuration and in the energy evaluation of energy-related products, such as household appliances.

This research thesis wants to overcome this lack and develops an eco-design methodology and related tool able to assist product designers in ecological design choices and in the integration the eco-design regulations into the design process. This work aims at integrating eco-design with the traditional design activities. The proposed approach has been applied to the household appliance field, but it can be easily extended to other mechatronic products.

This research thesis develops an eco-design approach driven by virtual prototyping and knowledge management to support the development of sustainable products. The objective is to support engineers in ecological design choices during early phase of product design, by collecting and making available guidelines and eco-knowledge in a structured database that integrates information related to eco-design and virtual prototyping. This means that environmental parameters associated to the product can be identified and evaluated during the early design phases together with product performances. The consultation of the eco-knowledge stored in the database has to be simple and has to rapidly allow the evaluation of possible alternatives design solutions. These alternatives can regard shapes, dimensions, materials to be used, performances and many other factors. The final result, proposed within this work, is a framework which propose through the consultation of the database a guided design process towards eco-design. The database can be automatically updated time after time new design solutions are conceived in order to create knowledge. The updating of the database enables designers to create eco-knowledge in order to evaluate different design choices easily and dynamically during early product development phase. A prototype of the tool and the database highlights the benefits introduced by the application of the approach.

This research thesis is part of a broader research project in which important national and international companies were involved. Specifically, the work carried out to gain the objectives can be summarized in following parts:

- definition of the methodology for the knowledge management tool;
- definition of technical and functional features of the guidelines tool;
- definition of the content of the database and classification of guidelines;
- definition of the methodology of virtual prototyping to reproduce energy consumptions test through the use of virtual models for the case study products;
- definition of the structure and execution of experimental tests in order to validate the virtual models;
- experimentation and validation of the methodology in the industrial context;

1.2 Overall context of the research work

In the last decades, studies and researches have highlighted the increasing importance of sustainability in products and services. According to different works from the United Nation Environment Program (UNEP) and other organisations, the level of consumption of natural resources will be unacceptable due to the global population growth, the consumption growth in developed countries. Furthermore, the resource depletion is not the whole problem, because the climate change is the greatest environmental trouble. The protection of the environment has been an increasing preoccupation since seventies, due in particular to resources crisis, acute pollution events, or wider political strategies.

In industries, the traditional "end-of-pipe" approach of the seventies aiming at treating liquid, solid and gaseous effluents, has expended during the eighties and nineties into a more preventative approach, called "middle-of-pipe" which consists in minimization of waste and energy consumption. During the nineties, the challenge to the prevention of pollution enlarged the attention to the whole lifecycle of products and materials through the development of product eco-design. The approach "Eco-design" is defined as the systematic integration of environmental considerations into product or process design. Eco-design aims at designing a product or a system considering the negative effects on the environment through the whole life cycle of the product in order to reduce them without altering quality or performances.

Legislation is an important driver for eco-design development as European Parliament passed many regulations and directives which define common rules concerning technical issues, financial issues as well as essential prevention dispositions that encourage eco-design. Eco-design plays an important role also in companies, in fact today, is an essential topic of sustainability policy in companies. A growing environmental awareness has arisen among consumers, leading them to a perceived generalized positive attitude on product green label (Laroche et al., 2001). As consequence of environmental policies and laws which are focused towards the eco-sustainability dimensions, Industrial firms and companies tend to produce products compliant with these directives and provide the market with more sustainable products. (Swenson and Wells, 1997).

Energy and environmental policies are important factors which influence the environmental consciousness of industrial companies. The attention to the environmental dimension is rapidly becoming a fundamental product design focus in a variety of industries. Nowadays, industries are changing their product development strategies to more sustainable models. (Favi et al., 2012). Eco-design has an important role in the reduction of the environmental impacts of the products because encourages a global approach designed to prevent or minimize impacts emerging throughout the whole lifecycle of products and concerning all types of environmental impacts (Le Pochat at al., 2007). Indeed, the design phase is an important phase of the product life because from an environmental point of view decisions taken during this phase have a significant effect on the product environmental impacts.

Several eco-design approaches and tools have been proposed and developed in recent years to support designers during all stages of product design process (Navarro et al. 2005). Generally, these solutions can be classified into three categories: quantitative environmental assessment often used in detailed design phase or for a product redesign, qualitative tools such as “guidelines” used at the conceptual design phase, even if they do not return quantitative indications to designers and indicators developed to provide a reference to ensure compliance with standards and guidelines.

Despite the great number of tools and methods, the use of these solutions is still limited. Tools and methods often are too far from industrial necessities and require expert personnel due to the specific knowledge requirement (le Pochat et al.2007). Literature shows a discrepancy between the tools and the working practice of designers and a difficult integration into the traditional design process (Lofthouse 2006). The challenge of the research work lies in the implementation of eco-design in the design process.

1.3 Technical and Research Objectives

This research work aims to propose a transition towards a real integration of eco-design in design processes. Designers and engineers work to increase product performances and often they overlook the environmental aspects due to the complexity of tools or the difficulty to integrate the methodologies into the standardized product development.

The first objective of this proposed work is to create a comprehensive framework combining existing design tools (e.g. CAD, VP) and environmental requirements and able to support the designer choices throughout the industrial product development.

The idea leading this research work is to integrate principles of eco-design such as laws, mathematical models, and thresholds in a virtual environment. The inputs derived from all the figures involved in the product design process can be satisfied in order to create a common strategy and to get the environmental achievements in the eco-design matters.

The second objective is the development of a structured repository for the collection, classification and efficient sharing of eco-knowledge able to store all the useful information for the development of sustainable products.

The eco-knowledge is constituted by environmental guidelines, all past choices made by designers during the design process and choices related to product/process data and simulations (materials, dimensions, strategies, etc.). Through the repository of knowledge engineers and designers can increase their awareness about product performances, features and sustainability aspects and can reuse this information during the actual or future design processes.

The third objective is the creation of a virtual model (specific for each product) able to simulate energy and environmental performances in compliance with eco-design and energy labelling standards.

The development of virtual models allows to analyse the energy performances and the use phase in compliance with eco-design standards. The virtual model aims to overcome the current issues for designers who develop mechatronic products (long trials, personnel costs, equipment, materials and limited number of tests). In this respect, the methodology involves the use of virtual prototyping techniques to recreate, in virtual environment, analysis that, otherwise, require experimental testing. The novel aspect of the introduction of the virtual model is the possibility to make more awareness the designer about their design choices.

The fourth objective is the creation of an eco-design tool which can guide the designers in the eco-sustainable choices in the first phase of product design process.

The approach will provide rules, contextualized guidelines and analysis from previous study, and so the designers will be supported in their decisions more quickly. In the decision-making problems, designers need to define the problem under study, and they need to assess the risk of different objectives to reach with respect to different environmental attributes. They can evaluate each choice from an environmental point of view following the precise indications of the tool and can evaluate the applicability of them in order to model the specificity of the tool on product and company requirements.

1.4 Research Methodology Developed

The approach of this PhD project is inspired from the Design Research Methodology (DRM) referring to Blessing and Chakrabarti framework (Blessing and Chakrabarti, 2009) which provides a flexible framework for design research in order to improve the chances of producing a successful product. In fact, although design is one of the fastest growing areas of research, the status of research into its own research methodology is poor. There is the need to develop a common research methodology.

In this context the main aims of the DRM are to help researchers in identification of the issues of the design research activities. Design is a complex activity, involving artefacts, people, tools, processes, companies, environmental issues and different context in which this takes place. Design research aims at increasing understanding of phenomena of design in all its complexity and at the development and validation of knowledge, methods and tools to improve the observed situation in design.

Design research can be considered to have passed through different phases as experiential, intellectual and experimental, but in all phases a theoretical framework to incorporate all phases is needed. The DRM covers all these phases, considering both the study of the phenomenon of design as well as the development of design support.

The two principal objectives of a Design Research Method (DRM) are "the formulation and the validation of models and theories about the phenomenon of design, and the development and validation of support founded on these models and theories, in order to improve design practice, including education, and its outcomes".

These sentences show the objective of improving an existing situation, which conduct to the description of the as-is situation, the modelling of the to-be situation, and the definition of a medium that has the possibility to change the existing situation in ideal situation.

According to a DRM, the overall aim of design research is “to make design more affective and more efficient, in order to enable design practice to develop more successful products.”

The DRM consists of four steps which are not a set of stages and supporting method to be executed rigidly and linearly and which can be summarized as Research Clarification, Descriptive Study I, Perspective Study and Descriptive Study II.

- Research Clarification (RC) stage is essential to determine the aim, focus and scope of the research project.
- The Descriptive Study I (DS-I) stage aims at increasing the understanding of design, to elaborate the initial description of the existing situation and to inform the development of a support.
- The Prescriptive Study (PS) stage aims at developing a design support. This support can be a new method or tool that is expected to provide a practical benefit to the research objectives.
- The Descriptive Study II (DS-II) stage focuses on evaluating the usability and applicability of the support and its usefulness.

Figure 1 shows the links between these stages, the basic means used in each stage and the main outcomes. The bold arrows between the stages illustrates the main process flow, the light arrows the many iterations. A specific research project will not necessarily include each stage or undertake each stage in equal depth. In fact, Blessing and Chakrabarti specify that “DRM is not a set of stages and supporting methods t be executed rigidly and linearly”;

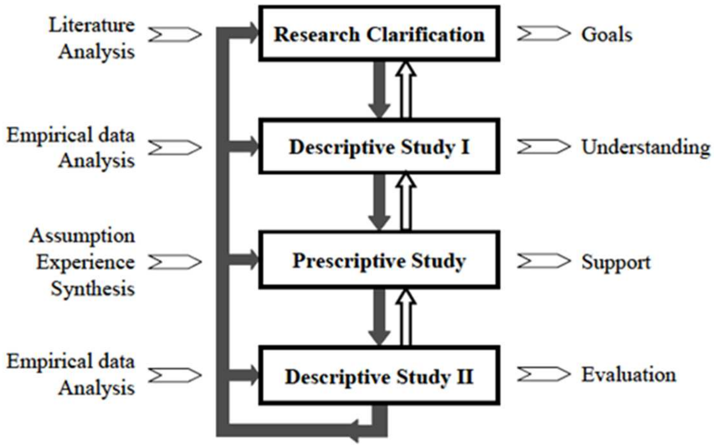
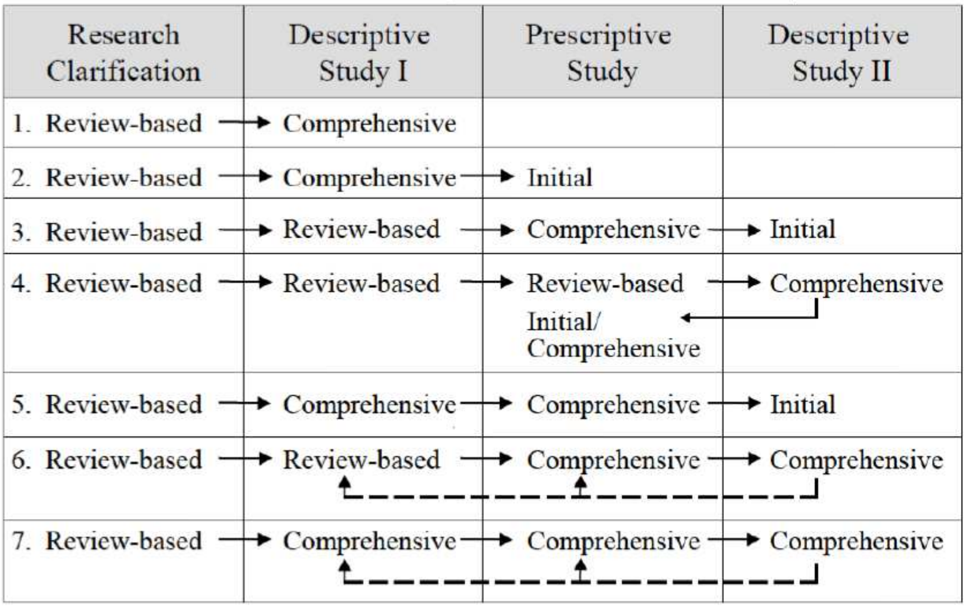


Figure 1 - Overview of the Design Research Methodology (DRM)

Blessing and Chakrabarti lists seven possible types of research depending on the research question and hypotheses, the available time and resources. It means that for a particular research project a comprehensive study could be required, or a review-based study could be sufficient. A review-based study consists in a review of the literature while a comprehensive study involves a literature review and a study in which the results are produced by the researcher. An initial study ends a project and consists in the first few steps of a particular stage.



Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1. Review-based	Comprehensive		
2. Review-based	Comprehensive	Initial	
3. Review-based	Review-based	Comprehensive	Initial
4. Review-based	Review-based	Review-based Initial/ Comprehensive	Comprehensive
5. Review-based	Comprehensive	Comprehensive	Initial
6. Review-based	Review-based	Comprehensive	Comprehensive
7. Review-based	Comprehensive	Comprehensive	Comprehensive

Figure 2 - Types of design research projectsand their main focus

PhD projects in 3 to 4 years in research design usually follow the first types of research because of time and resources constraints. This work is a type of research 3. Each stage is described below, referring to Figure 3 summarizing the general research approach and the thesis chapters.

Research Classification (RC)

The design process has to consider the environmental constraints early and throughout the whole design process. An analysis of the different specificities of eco-design integration realized in the chapter 2 reveals that the environmental aspect is not an easy viewpoint to integrate. This works aims to highlights the challenges of eco-design integration and how to remove them.

Descriptive Study (DS-I)

Through a literary review, the research work highlights different weakness and key element to achieve the research goal consisting in the creation of a structured framework able to integrate eco-design into the design process; through the literary review the problematic is presented, and the objective is to transform the weakness into working hypothesis (functions) in order to develop the methodology. According to the key element identified in the literary review, the research methodology develops four working hypotheses representing the function of the methodology for an effective integration of eco-design. The functions are related to:

- Integration;
- Eco-knowledge creation;
- Decision making support;
- Simulation;

The problematics and the working hypothesis of this research work and of the methodology are exposed in Chapter 3.

Prescriptive Study (PS-I)

The proposal is built on these functions. The goal is to propose a solution which satisfies these functions. The work proposes an eco-design approach driven by virtual prototyping and knowledge management to support the development of sustainable products. The proposal would support designers in ecological design choices since the early phase of product design process. The proposal is presented in the Chapters 4 and 5.

Descriptive Study (DS-II)

In order to validate this proposal, the methodology has been applied to a specific case study and two experimental phases are carried out in different industrial contexts, focusing on particular phases of the design processes. The experimental phases are presented in the Chapter 6. Limits and points of strength of the proposal have been identified during these experimental phases. Considering the function verifications of the proposal during the experimentation, the conclusion is that eco-design in industries is stimulated by four main aspects: integration in the traditional design process, necessity to create eco-knowledge, need to support the decision making during the design process and use of tools to simulate performances of product.

The conclusion of the work conducted in the research thesis is presented in Chapter 7 with a summary of the contributions and a list of perspective.

1.5 Thesis Overview

The thesis is organized in chapters following the Design Research Methodology explained previously as presented in Figure 3.

Chapter 1 – illustrates a brief introduction of the research work and the main developed topics. The overall context is presented to focus the attention on the main problems concerning eco-design and its integration in the design process and how to overcome them. The technical and scientific objectives of the proposition are briefly described and explained, and the research design methodology developed for this work is presented.

Chapter 2 – presents a general overview on the research context putting the attention on the main problems concerning product development process and eco-design.

Chapter 3 – presents a literary analysis of the different specificities of eco-design. The state of art reveals that the environmental aspect is not an easy viewpoint to consider into design process. The challenges of the eco-design can be summarized in four main points which are the integration, the creation of eco-knowledge, the use of eco-design tools for the evaluation of product performances and the need of a concrete support in the decision-making process. This literary analysis has helped to draw a precise picture of the existing situation and to understand the weakness of the actual design methodologies in order to transform these weakness as principal features of the proposed PhD project.

The image (Figure 3) shows the link between the DRM stages and the thesis chapters.

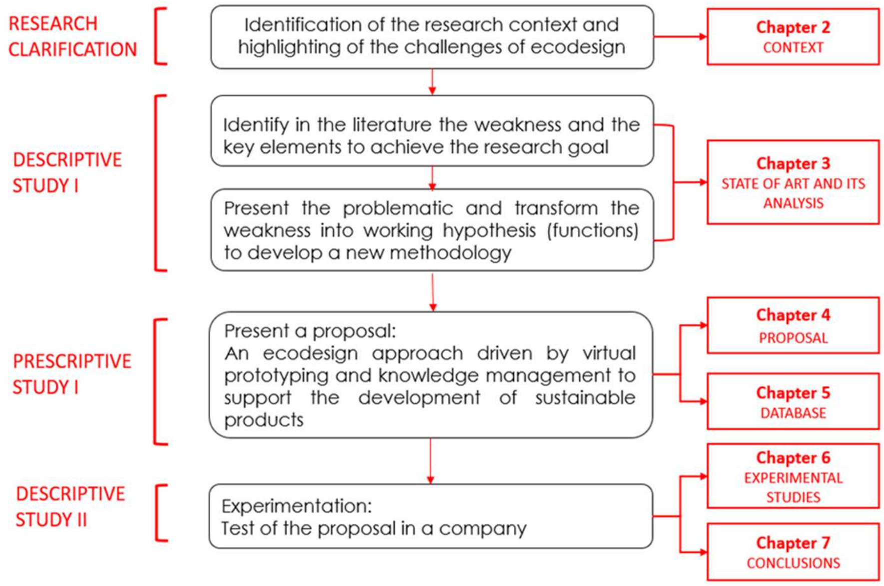


Figure 3 - Synoptic of the research approach

Chapter 4 – describes the proposal of the PhD project: a new structured methodology and related tool called *virtual eco-design* (VE). VE framework aims to support designers and engineers in the development of environmentally sustainable products, taking into account eco-design regulations since the early phase of product design with the help of a structured database.

Chapter 5 – describes the structure of the database presented in the approach and deepen the content of each section.

Chapter 6 – presents the description of the methodology application on a specific case study (induction hob). The methodology has been applied following two phases of experimentation where each of them focuses on a particular phase of the design process, in order to identify benefits and limits of the proposal.

Chapter 7 – presents conclusion and future work on the proposed research activities and results and leaves an “open door” to future development.

Chapter 2.

Context of research

2.1 Product Design: a verb to create new products

2.1.1 The traditional engineering design process

The engineering design process is a series of steps that engineers follow to come up with a solution to a problem. Many times, the solution involves designing a product that requires certain criteria and/or accomplishes a certain task.

In literature, one of the most important studies on design methods to conceive and develop industrial products is proposed and summarized by Pahl and Beitz (Pahl and Beitz, 1996). They identify, as follow, the four main phases for product development process:

1. *Planning and Task Clarification*: to collect information about the requirements that have to be fulfilled by the product, and also about the existing constraints and their importance. The results of *Task Clarification* are the definition of design specifications.
2. *Conceptual Design*: to abstracting the essential problems, establishing function structures, searching for suitable working principles and then combining those principles into a working structure. *Conceptual Design* results in the specification of a principle solution (concept).
3. *Embodiment Design*: to determine the construction structure (overall layout) of a technical system in line with technical and economic criteria. *Embodiment Design* results is the specification of the product layout.
4. *Detail Design*: to define the arrangement, the shape, the dimensions and surface properties of all individual parts which compose the product, the materials specified, production possibilities assessed, costs estimated, and

all the drawings and other production documents produced. The *Detail Design* result is the specification of information in the form of production documentation.

It is not always possible to draw a clear borderline between these main phases. For example, aspects of the layout might have to be addressed during conceptual design, or it might be necessary to determine some production processes in detail during the embodiment phase. Neither is it possible to avoid backtracking, for example during embodiment design when new auxiliary functions may be discovered for which principle solutions have to be found. Nevertheless, the division of the planning and control of a development process into main phases is always helpful. The working steps proposed for each of the main phases are termed the *main working steps.* Figure 4 shows the main four steps of the described engineering design process proposed by Pahl and Beitz and summarizes the main activities for each phase.

The main purpose of the Planning and Task Clarification phase is to generate new ideas and new concepts of a technical and non-technical nature. The design department focuses on developing new product concepts to challenge and complement strategic business (Svengren, 1997). Designers and engineers provide new technological innovations that can be integrated into product development. The product proposal is defined based on the task that are clarified and the functional requirements that are elaborated. Design concepts generated at this stage may or may not be based on reality. The list of product specifications is the important starting point for all the following working steps. The product specification shall comprise all quantitative and qualitative data and all serve as a basic document for any product development process.

During the *Conceptual Design* phase, the design process is rapid and interactive. Once industrial designers have been given a brief for a project, they “pick it up and run with it”. Often, their first hunches for solutions are drawn from their stored tacit knowledge, gained from previous design projects and from design education. They use mood boards to stimulate and contextualize the design, and to create a “sense” of the product. Ideas are generated through the use of individual and brainstorming group sessions. This design stage typically involves: the production of sketches, drawings, mock-ups or models to test basic technical feasibility, assess proposed production methods, etc. (Ulrich and Eppinger, 1995). It is worth noting that core designers may also have some input into the *Conceptual Design* phase if this is appropriate for the product under development.

The next phase in the design process is the *Embodiment Design* stage during which the design is developed, and scope is added to the initial concepts. This is where the main role of core design is to be found. During this stage, designers investigate competitor’s products by taking them apart to see how they work and how they are manufactured. Concepts have been embodied through the use of 2D sketches, CAD models, layout drawings, schematics and mock-ups.

Mock-ups and/or prototypes have been used to test technical principles such as users’ needs, component configuration and manufacturing capabilities, visualize layouts and ensure that styling encourages a certain use (Ulrich and Eppinger, 1995). Performance calculations and decisions on materials and finishes have been also made at this stage. For instance, the most important technical analysis performed at this stage is the refinement of cost effectiveness.

At some point during the *Detail Design* phase, core industrial design hand over the project to design engineering, depending on the nature and complexity of the project. Within this stage, industrial designers and design engineers use manufacturing and material knowledge to ensure that designs are efficient and profitable to produce and issues such as safety and usability are refined. By the end of the stage, the working drawings that provide information on the materials selected, tolerances and manufacturing processes, are passed onto the production elements of the product development phase. Finally, the product enters in the manufacturing level, where design engineers liaise with the production team.

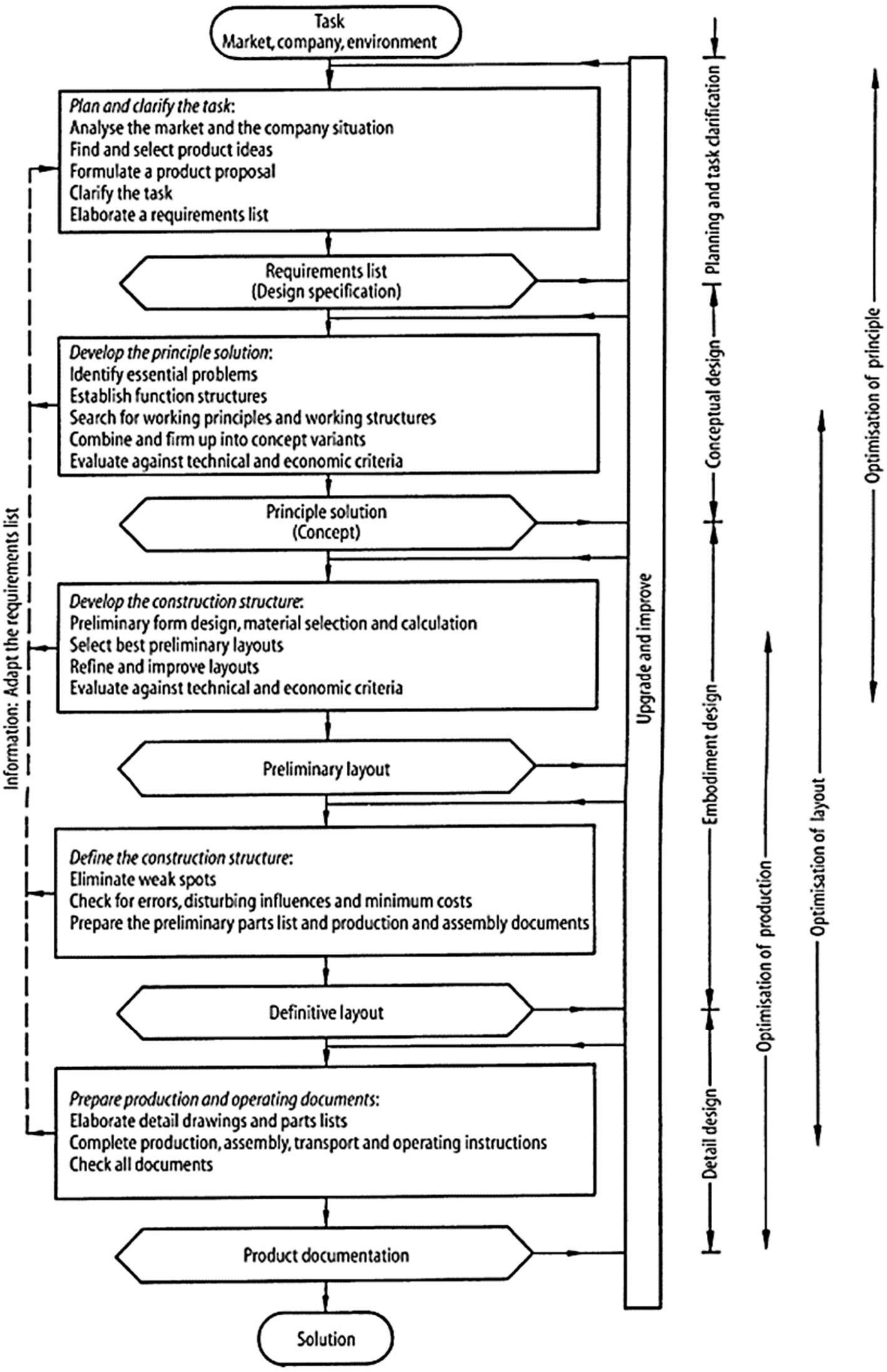


Figure 4 - Steps in the planning and design process

2.1.2 The product design process

Companies are looking to shorten the product design cycle and designers are constantly searching for ways to quickly assess initial ideas and determine product feasibility before precious time and resources are devoted to development.

The creation of a functional modelling is the way to put into practice the described approach of the design process proposed by Pahl and Beitz (Pahl and Beitz, 1996) and revised by Stone (Stone at al., 2000).

The most important aspect during the development of a product is the function that the product has to deliver in order to fulfil a need.

Design tools, such as functional modelling, can be utilized in the early stages of design while the project requirements or customer needs are being determined and refined. Functional modelling allows design teams to systematically represent a design within a universal framework. Functional modelling is widely used and allows complex problems to be abstracted into a form that is easily solvable. When utilized in a capstone design course, functional modelling equips student designers with an objective method of representing complex systems based on the functions they will perform. The advantage of the functional modelling is the possibility to assess the product behaviour since the early phase of the product design such as Conceptual design phase when the product is conceived by designers. Furthermore, modular analysis is a systematic and repeatable approach which can be used for product design and analysis. The approach, oriented to product modularity, is strongly dependent upon functional characteristics of the product and their mapping on its physical assembly structure and architecture. The product function model, corresponding to the specific product functions, is closely related to the customer's needs. The functional approach which meets the customer's needs and function specifications are called the function-based modular design (Hirtz et al., 2002).

The first task of the functional model derivation is to create a Black Box model, a representation of a product's overall function and input/output flows. The overall function of the product is expressed in verb-object form. Each customer need identifies one or more input or output flows for the product (Stone and McAdams, 2004). In particular:

- *Material flow:* it's usually referred to a material that has characteristic of form, mass, colour, etc. Materials can be mixed, separated, finished, transported, etc. Gas, liquid, solid, dust, row are typical example of material flows.
- *Signal flow:* it's the internal capacity to decide of a sensor or device. Signals are generated, separated, received, transmitted or stored.
- *Energy*: it's the capacity to modify material motion or condition. It can be electrical, kinetic, magnetic, optic and heat.

Figure 5 - "Black Box" model

The method of module heuristics consists of three separate strategies to identify modules:

- Dominant flow
- Branching flow
- Conversion-transmission modules (Stone et al., 2000)

Using this formalism, the main function is divided into sub-functions and a complex-tree can be structured.

The module heuristics identify the in/out flows of each sub-function. By using this approach, it is possible to translate the product functions into functional modules. Functional modules define a conceptual framework of the product and the initial product configuration. Furthermore, heuristics allows determining the specific properties of each functional module.

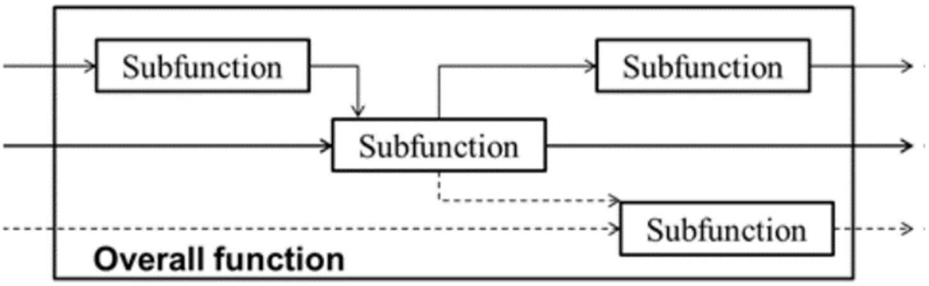


Figure 6 - Formalism used for division into sub-functions

The transition from product modules to potential design solutions is based on the knowledge of specific properties identified during the generation of the product modules (Pahl and Beitz, 1996). The generation of product module lead designers to the concepts of modularity which has great effects on product manufacturing, assembly and disassembly.

A very helpful tool at this step is the morphological matrix which can improve the effectiveness of the conceptual analysis and translates functional modules to physical modules (Jansson, 1990). A morphological matrix is traditionally created by labelling each line with all the identified product modules and, for each module, the possible design options, listing the solutions as columns and the product module as rows. The morphological matrix finally shows existing alternative design options for each functional module of complex system and it permit a rapid configuration of the product with the selection of the best option for each specific module (Zwicky, 1948).

The great advantages of using a functional basis model for the development of industrial products are:

- systematic approach for product design and analysis
- objectively quantifying the degree of product modularity
- increasing the possibility to substitute modules during product
- use (maintenance)
- customized product (Increasing the function portfolio provided
- to consumer)
- easy to re-design approach
- reducing assembly/disassembly time and operations
- reducing time-to-market.

2.2 The Eco-design: a new way to design

The first wave of sustainability has been introduced since the 1970's, when designers such as Victor Papanek began to link the environmental matters to the production. (Papanek, 1971). Since then a lot of eco-design tools and methodologies have been developed to support designers during the design process (Navarro et al., 2005).

Currently, mechanical designers provide technical solutions to meet companies' and customers' requirements such as the function to perform, the cost of the product, or its ability to be mass produced. However, increasing focus on the environmental issues leads to looking at new requirements and forces product designers to consider environmental criteria in the design process (Ilgin & Gupta 2010). Despite this methodological development however, literature around the topic still points to a disappointing lack of successful and entrenched examples of commercial eco-design (Knight and Jenkins, 2009). The reasons given for this discontinuance vary from a misalignment between the tools and the working practices of designers, to a failure to support eco-design from a wider business perspective (Lofthouse, 2006).

The standard ISO/TR 14062 (ISO 14062 2002), related to environmental management, defines eco-design as the “integration of environmental aspects into product design and development”.

In literature surrounding this research area, there is a range of terms closely referring to this definition. These terms include environmental product development (EPD) (Baumann et al. 2002), green design, eco-design (van Hemel & Cramer 2002; Gottberg et al. 2006), environmental design, design for the environment (DfE) (Lenox et al. 1996), life cycle design (Vezzoli & Sciama 2006), and sustainable design (Ramani et al. 2010).

All definitions can be included in the general one of the standard ISO but some authors add characteristics or specific viewpoint.

The description given below by Johansson introduces the inclusion of lifecycle thinking inherent in any eco-design project and the inclusion of the environmental considerations alongside the traditional design issues:

“*The term eco-design refers to actions taken in product development aimed at minimizing a product’s environmental impact during its whole lifecycle, without compromising other essential product criteria such as performance and cost*.” (Johansson, 2002).

Van Hemel and Cramer (van Hemel & Cramer 2002) express also this concept:

“*By ‘eco-design’ is meant the systematic and consistent strife for improving the environmental profile of product(s) in all stages of the product life cycle, including proper recycling and disposal.*”

Other authors, such as Pigosso and Sousa, define ecodesign as a management activity:

“*Eco-design is a proactive management approach which directs product development towards environmental impacts reduction along its lifecycle.*” (Pigosso and Sousa, 2011).

Definitions of eco-design are also given through the determination of the boundaries of eco-design against the wider context. This exploration of Eco innovation offers a very clear distinction between five levels of environmentally inclusive design; sustainable design, Environmentally Conscious Design (ECD), eco-innovation, eco-design and Design for Environment (DFE). O’Hare places these five terms on a sliding scale that relates to their ambition, scope and environmental impact and summarizes this scale as such:

“*DFE integrates environmental considerations into product design but focuses on one phase of the product lifecycle; eco-design broadens this to consider the entire product lifecycle; eco-innovation extends eco-design into the early stages of innovation; ECD is an umbrella term for DFE, eco-design and eco-innovation; and sustainable design is any form of ECD that considers social and economic aspects of sustainability as well as the environmental aspects.” (O'Hare, 2010).*

In contrast writers, such as Karlsson and Luttropp, define eco-design as “Product Design for Sustainability”, placing it in the wider context and discussing it as tool or step that contributes to an overall goal.

“*Eco-design is an aspect of design, a new smart design for the future in line with the Bruntland report statement that a sustainable future fulfils today’s needs without jeopardizing future generations’ possibilities to reach their own goals*”
(Karlsson and Luttropp, 2006).

In addition, Karlsson and Luttropp explains in figure the linguistic roots of the word Eco-design and shows the similarity with economy and ecology (Karlsson & Luttropp 2006).

Figure 7- Linguistic roots of the word "eco-design"

This definition coincides with other writers on sustainability such as White et al., who offer this image as a representation of the transition required to move from traditional design to sustainable design and describe this change as “an on-going learning process” (White et al., 2008).

2.3 Policies oriented to industrial sustainability

2.3.1 An overview on environmental policies

In 1997, more than 180 Countries signed the International Environmental treaty “Kyoto Protocol” (Almer and Winkel, 2017) to counteract climate change on our planet. After the Russian ratification in 1995, the Protocol provides for an obligation to reduce polluting emissions to 8% compared with the 1990’s emissions. Giving continuity to this treaty, in 2009 the European Union (EU) developed the EU 20-20-20 Energy and Climate Package with three specific objectives: (i) to have 20% reductions in greenhouse gas emissions compared to 1990 levels, (ii) to reach 20% of the energy, on the basis of consumption, coming from renewable sources and, (iii) to obtain an increase of 20% in energy efficiency. Scientific research and institutions have shown a growing importance of concerns relating the energy efficiency and in general to the concept of reduction of energy consumption, which are considered key means for reducing greenhouse gas emissions (GHGs).

Nowadays, environmental policies are an important instrument for the development of sustainable products. The new policies oriented to industrial sustainability and energy efficiency are the result of a negotiation policies. In this context, household appliances represent 25% of total European energy consumption (EEA, 2013). It is therefore very important to increase the purchase of products with high efficiency and low energy consumption. The EU is now facing unprecedented challenges resulting from increased dependence on energy consumption and scarcity of energy resources, the need to limit climate change and at the same time to overcome the economic crisis. Energy efficiency plays an important role in addressing these challenges.

The Eco-design Directive (2009/125/EC) and energy labelling Directive (2010/30/EC) has been one of the most effective policy instruments at EU level to promote energy efficiency, estimated to contribute around half of the energy savings target for 2020.

Eco-design Directive (2009/125/EC) formalizes eco-design requirements for energy-using appliances and Energy Labelling Directive (2010/30/EC) defines minimum requirements to assess product energy efficiency during the use phase. Those standards are two milestones for setting mandatory ecological requirements.

The Eco-design and Energy Labelling legislative framework has the dual purpose of ensuring that more energy-efficient products come to the market (through eco-design) while encouraging and empowering consumers to buy the most efficient products based on useful information (through energy labelling). By doing so, it reduces the energy consumption of consumers and businesses, and thereby their energy and utilities bills. Furthermore, it safeguards the internal market and prevents unnecessary costs for business and consumers due to divergent national requirements.

Through these Directives and their implementing measures, the EU sets energy performance requirements and related energy labels for a wide range of energy-using products. The specific requirements for each product group is setting by specific regulations, which are defined after preparatory studies and extensive stakeholder consultation phases, such as delegated acts for energy labelling, implementing acts for eco design. Eco-design Directive was adopted in 2005 and recast in 2009, while Energy Labelling Directive was adopted in 1992 and recast in 2010. The object of these programs is to save energy by transforming the market, stimulating the offer and the uptake of products, supporting consumers in purchase of more energy efficient products. Energy Labelling and Eco-design Directives complement each other, promoting the best products from an energy efficiency point of view. The purpose of the Energy Labelling Directive (2010/30/EU) is the strengthening of synergies between existing legislative measures, in particular with them linked to the Directive Framework 2009/125/EC.

2.3.2 The EU Energy Labelling Directive: positive aspects and limitations

Energy Labelling Directive allows the Commission to require energy labels displayed on energy related products at point of sale. Labels (Figure 8) show energy performances (consumption) and which energy class a product achieves, in order to encourage the sale of more energy efficient and environmentally friendly models. After a preparatory study, a regulation related to a product family is drafted, detailing the energy label for the specific group of products belonging to this family.

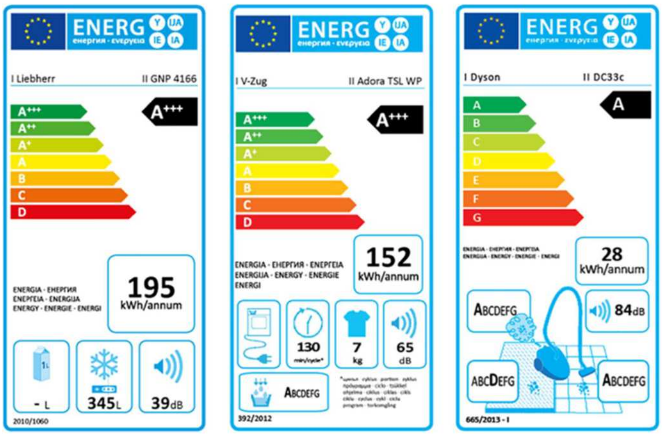


Figure 8 - The EU Energy Labelling Directive

EU Energy label is physically attached to appliances in stores and contains the following information:

- *Energy efficiency class*: the energy efficiency of the appliance is described in terms of categorical, alphabetical rating scale. This scale covers a large part of label and it is highlighted thanks to a colour code from green to red. The scale has a range from A to G, where A means the most energy efficiency and G the least efficiency. During last years, to bring out new energy efficiency results gained, there was the introduction of A+, A++, A+++ classes on top of A-G scale. The EU directive provides that, until 2020, classes of greater energy efficiency will be introduced every two years. Therefore, the A+++ class will be achieved in 2020.
- *Energy efficiency Indices*: the energy efficiency classes are based on several energy efficiency indices that are calculated separately for each product category. In addition to values of different parameters, there is an information on the expected annual electricity use of the appliance in kilowatt hours (kWh), based on standard testing by manufacturers. This value corresponds to a

"default" electricity consumption value for a phase-use defined in the standard testing procedure.

Making a summary of previous information, the EU energy label presents a set of information and a rating scale for an appliance's energy efficiency, supported by graphical and colour design. Nowadays, eleven delegated Regulations ensure that a range of products, which are also subject to Eco-design Regulations, must be sold with an EU energy label attached. All these measures were updated in 2014 and from this date the energy label will also be shown when selling the product via the internet.

Labelled household appliances and relative Regulation established by Directive 2010/30/EU are shown in Table 1:

N.	Product type	Regulation
01	Dishwashers	UE Regulation 1059/2010
02	Refrigerating appliances	UE Regulation 1060/2010
03	Washing machines	UE Regulation 1061/2010
04	Televisions	UE Regulation 1062/2010
05	Air conditioner	UE Regulation 626/2011
06	Household tumble driers	UE Regulation 392/2012
07	Vacuum cleaners	UE Regulation 665/2013
08	Domestic cooking appliances	UE Regulation 65/2014
09	Electrical lamps and luminaires	UE Regulation 874/2012
10	Heaters	UE Regulation 811/2013
11	Water Heaters	UE Regulation 812/2013

Table 1- Household appliances Regulations

From the analysis of the current literature situation, as well as from the experience obtained from reports and actual implementation of the Energy Label Directive, a series of positive aspects and limitations result.

Energy label positive aspects

On the basis of the outcomes of the study, we have identified potentialities related the EU Energy label. At first, it is important to highlight that EU Energy label is an important established instrument to provide information and raise attention to energy consumption characteristics of household appliances. This aspect helps consumers to make better purchase choice for themselves and for the environment, allowing them to choose more efficient products. Following the introduction of A+ and higher classes, labels have become more effective in persuading consumers to buy more efficient products (Stadelmann et al.,2018; Carroll et al., 2016).

Energy labelling plays an important role in the increase of energy efficiency and protection of environment. It improves the EU’s security of supply by reducing primary energy consumption and decreasing energy imports. The competitiveness of industry and its impact on the innovation is strongly improved by the introduction of energy label, in fact it boosts the economic growth, alongside consumer demand and competitive position, creating high quality job in several sectors related the energy efficiency (Ambec et al., 2011; Ashford et al., 2011).

The EU is strongly involved in the development of minimum energy efficiency requirements and energy labelling. The EU energy label has increased the profile and the importance of product energy efficiency overcoming information barriers and making available environmental matters to majority of consumers (Davis et al., 2016). Using obvious and mnemonic schemes composed by the color scale and letters, to indicate the different efficiency scale, it has reinforced the approach of users to energy efficiency products (Hille et al., 2017). In the label scale, in fact it is clear the highest and the lowest part of the scale and where the efficiency of the specific labelled product is positioned. The mnemonic aspect is important to support memory in keeping information about which product to buy.

Another important factor is the involvement of stakeholder, consisting of a series of actions and participation of interest groups (i.e. representatives of manufacturers, European authorities, civil society organization and business) in a planning or in decision-making process of the labelling matters. This involvement represents a great value to the labeling process because of its support in transparency, information and discussion about several practices (Ecofys, 2014). The importance of labeling increase in the household appliances, in fact the most important aspect of energy label impact is mostly addressed to the use phase which represents the most important contribution to the environmental impacts (Rohling et al., 2013; McNeill et al.,1979) looking at the life cycle perspective. Different studies have shown that the Energy Label Directive is effective (Wang et al., 2017; Wiel et al., 2005) providing significant benefits to consumers in terms of monetary savings, to industry in terms of design innovation and competitiveness and to the environment in terms of reduced impacts (Mahlia et al. 2010).

Energy label limitations

The literature analysis conducted on this issue, has allowed identifying also some criticalities and limitations related to EU Labelling Directive. The first aspect to underline, as suggested by Mahlia (Mahlia et al., 2010) is that the majority of publications related to standards and labels concerns the situation of developed Countries, while few publications are focused on those one related to developing ones (Egan et al., 1998).

In the EU Labelling Directive, the ISO procedures for test realization, definition of parameters and setting options is adopted (Turiel, 1997). However, some criticalities can be identified connected to this aspect. In particular, by overturning the proposition of Meier and Hill (Meier et Hill, 1997) for a good test procedure, it is possible to underline that energy label tests actually not reflect real usage conditions. As an example, for the induction plane case, specific and not common vessel must be used to derive energy absorption during the use phase. For the case of dishwashers and washing machines only one washing program is used to test the consumptions of the use phase (EU Regulation no 1061/2010).

Test procedures not cover several models of a product category, but differ from one to each other's, thus imposing company to realize multiple test sessions for each product.

Furthermore, tests are not replicable if few modifications are taken on a product, and they are usually expensive in economic, staff and time terms (Hinchliffe et al.2017). What emerges is that standard test procedures are a compromise (Wiel et al., 2001) between the need to derive ranking criteria and the need to respect company's constraints. Test procedures, which can replicate domestic use of products, will determine longer time and major costs, therefore, this option is not preferred (Meier et al, 1997), but it could increase the truthfulness of related energy data. Enter into the label, its style and format, they do not allow easy comparison with other models in the market (DuPont, 1998) and therefore limiting their effectiveness, which highly depend on what and how it's presented to consumers. Grankvist et al. (Grankvist et al.,2004) found in fact differences in consumer's response, depending on their viewpoint about environment issue and on the fact the label is "positive" or negative". They derive people with less environmental concern were more sensitive to "negative" labels, i.e. warnings which inform a product is disadvantageous from an environmental point of view respect to another one.

Looking to general sides, Ecolabel Directive focuses specifically on the energy aspect, thus neglecting the impact of all the other life cycle phases of products on the environment. This aspect can sometimes determine the neglecting of impact transfer processes, in particular when strategies to reduce use consumption are adopted. This is the case for instance of smart devices introduction for the control and reduction of energy consumption in household appliance sector. Despite it is supposed the use of smart devices mitigate environmental damages, several researches in recent years has also discussed possibilities of increased damages (L.M Hilty et al. 2006; Watson et al., 2012; Melville et al., 2014). Lack of data about the connection between ecolabel and improvement of environmental quality of society is recognized by several authors (Rubik et al., 2005).

To cover this gap, European Union has recently launched the Resource Efficiency Plan for a more sustainable use of limited resources, thus underling the importance to consider also the material and manufacturing phases of products. Another aspect that could be underlined is the specificity of test procedures for Countries, in particular for EU Countries respect to the others in the world. This aspect can represent a barrier for goods circulation (Hincliffe et al.,2017). However, the motivation is complex and lies in the fact some of the conditions in test procedures may not applicable in all Countries (Mahlia et al., 2002).

From the literature analysis, several positive aspects and limitations related to the implementation of Energy Label Directive have been identified. In particular, positive aspects and limitations can be grouped in three categories as presented in (Table 2):

- Test procedure, which involves all the aspects related to what the experimental tests analyse and the way they are performed;
- Label format and contents, which involved aspects related to visual information of the label and which is physically attached on appliances;
- Analysis realized, which involves aspects related to the typology of analysis realized on the product during the procedure tests and which allow to derive the reference parameters for the product.

Supported by the literature, and following the proposed approach, it is possible to collect into this schema some strategies which can allow to overcome EU labelling Directive limitations and to increase its effectiveness.

Strategies related to "test procedure"

- Improvement of repeatability and accuracy of tests and possibility to reproduce actual use condition (Mahlia et al. 2010).
- Harmonization of test procedures, target values and label information in order to stimulate international trade and to reduce related barriers (Hincliffe et al, 2017);

- Development of methods for the virtualization of test procedures, which can facilitate tests and reduce time and costs to conduct them. (Landi et al., 2016; Cicconi et al.,2017).
- Development of methods for the comparison of similar units of products (e.g. showing the energy consumption or of a particular model on a scale that also shows the lowest and highest energy consuming model).

Strategies related to "Label format and content"

- Possibility to face the increasing necessity to modify the label in order to take account of products with higher efficiency classes than products which have been labelled in recent years (Ecofys, 2014);
- Necessity to review the current energy label making a differentiation between current label classes and new necessary classes. These new classes can confuse the consumers and it is desirable to not add further + on top of the current A+++ class (Ecofys, 2013);
- Addition of a numerical color scale to the alphabetical one and quantification of each energy efficiency level with monetary and lifetime-oriented information values (Ecofys, 2014);
- Addition of clear indications in the label of how test results have been derived (i.e. specify product operational conditions) (O'Rourke, 2005);
- Providing 'transparent' and 'non-misleading' information on the label.

Strategies related to "Analysis realized"

- Improvement of graphics with a major stylization and simplification of the energy efficiency parameter icons, in order to help consumers in understanding them (e.g. the "switch logo" on the television label and the drying efficiency on the dishwasher label) (Ecofys, 2014);

- Introduction of additional negative environmental labelling schemes to better influence consumers with low environmental consciousness (O’Rourke, 2005);
- Introduction of additional not-energy related information, to extend consumer’s and producer’s attention also to other product life cycle phases (e.g. material, EoL); (Mahlia et al. 2002).

Category	Positive aspect	Limitation	Possible improvement
Test procedure	Based on international standards; Regulated from EU not dependent from manufacturers;	Specific for product Specific for country Different from real use condition Need to realize physical tests on products	Improvement of accuracy and repeatability; Harmonization of test procedures; Method development for virtual tests; Method development for comparison of similar products;
Label format and contents	Mnemonic; Alphabetical and color scale of efficiency classes; Overcoming information barriers;	No comparison among several models of the same product; Different perception for different consumers’ skills	Modification and review of label for higher efficiency products; Limitation of number of “+” in the high part of scale; Introduction of numerical color scale; Clear indication about test; Transparent information;
Analysis realized	Values of different parameters of energy efficiency; Annual consumption in kWh;	Focused on use phase; Entire product life cycle not included; Difficulties to quantify the real energy saving in monetary terms;	Improvement of graphics; Introduction of negative labelling scheme; Introduction of not energy related information;

Table 2 - Limitations and positive aspects of EU Energy Labelling Directive

2.4 Discussion

Sustainable design is no longer a new concept different studies and documents have been shown that a significant proportion of the environmental impact of the product is decided during the design phase. Sustainable design prompt designers and engineers to consider key factors for sustainability taking into account also economic and social considerations and aiming to generate solutions that consider the whole life cycle of the product. In fact, it would seem that a number of contemporary circumstances affect an increase in the significance and popularity of eco-design on an unprecedent scale. These circumstances are summarized as follows:

- The introduction of environmental requirements to compulsory legal regulations: for instance, with regard to energy-related products: the Eco-design Directive (2009/125/EC) and the Energy Labelling Directive (2010/30/EC);
- The intensification in recent years, on a European scale, of the efforts to popularize a way to thinking oriented to sustainable matters;
- The actions of European Commission to have a common scale to classify the energy and environmental performances of products (Energy Labelling Directive (2010/30/EC);

All of above-mentioned phenomena are contributing to the increase the interest in eco-design. In fact, as governments and regulatory bodies became more aware of the scale of environmental problems, they began to develop legislations to mitigate impacts. This regulatory influence has resulted in development of a common sensibility in the development of products which are more focused and directed to meet the specific targets of these legislations. In this context, the concerning impact of the use phase has highlighted a great potential for improvement of sustainability practices and a big influence on the behaviour of the consumers. In recent years has become evident that more frequent changes to product designs, rapid progress in manufacturing technologies and ever-changing customer demands are highlighting a need to rethink current practice. It is widely recognised that in order to respond to these factors, there is a need for a more flexible, responsive and agile design process which not only consider the product, but also the process.

The power of design to influence behaviours and transform industries has led to recognition that design will play a key role in helping to achieve more sustainable production and consumption.

Chapter 3.

State of the Art

3.1 The Specifities of Eco-design Integration

3.1.1 Integration of Eco-design in the design process

Nowadays environmental concerns play an increasing important role in society and companies which need to reduce the environmental impacts of their products. Consequently, the integration of environmental constraints early in the design process is a necessary prerogative. During last decade the research world has been addressed its efforts towards eco-design. The terms eco-design refers to actions taken in product development aimed at minimising a product's environmental impacts during its whole life cycle, without compromising other essential product criteria such as performances and costs (VanWeepen et al., 1995; Johanson et al, 2006;).

Eco-design is defined by ISO 140006:2011 as the integration of environmental aspects into product design and development with the aim of reducing environmental impacts throughout a product's life cycle. 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 analysed considering the integration of all environmental aspects throughout its life cycle (Curran et al, 1996). Eco-design integration, as presents Johansson, concerns a large number of aspects of product design and development. It is well-known that a large percentage of life cycle performances are determined by the product design, in particular early design decisions (Roper et al., 2006; Bhamra et al., 1999;).

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.

The integration of the environmental aspects in the early stages of the product design process is necessary to improve the design in term of environmental performances. In fact, eco-design forces designers, and even the wider company, to adopt a different view on their product. The designers have to consider, in addition to the usual technical criteria, the environmental technical criteria such as environmental toxicity, embodied energy, the disassembly, etc (Ritzen et al., 2000) Environmental matter must be considered among all other demands, tasks and requirements, as shown in Figure 9.

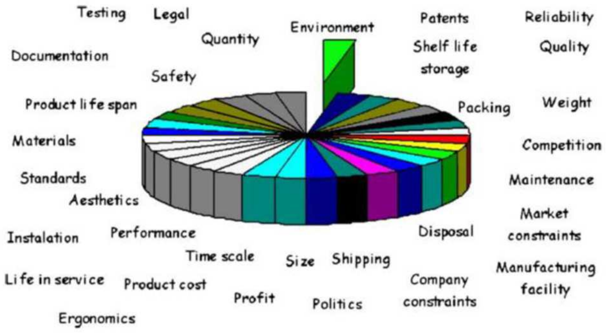


Figure 9 - Consideration within the design process

The environmental aspect lead designers and actors of product design process to create a networking among them in order to consider the environmental issue in all activities carried out, even with the support of an environmental specialist (Van Hemel et al.,1997; McAloone et al, 1996;). Company knowledge is recognized as a crucial element for the survival of industrial organizations and its sharing among different actors of design process is considered an element for the success of the organization.

The product environmental profile and most of factors that determine product final environmental performance, quality and cost are defined in the early design phase of the product development process. Bhamra at al stated that the critical point of the product development is the final setting of product specifications, because the technical properties are decided before and the environmental improvement properties are limited after the product specification, at the last stages of product design process (Bhamra et al., 1999).

Mascle and Zhao argued that during the initial design stages because up to 80% of the costs of product development, manufacture and use are determined. The design phase also determines the environmental impact that a product will have in the future life cycle phases, which implies specific information on material and energy flows in all life cycle phases but, this information is not known prior the embodiment or the detailed design phase. In the early design phases, in particular in the conceptual design phase, a description of the product is abstract and information about the environmental performance and life cycle is not available. The product during the conceptual phase can be considered incomplete and the knowledge about it is only qualitative and inconsistent. For these reasons, the knowledge about the environmental profile and performances is very low (Lagerstedt et al,2003; Sousa et al., 2006; Ullman et al., 2010). For these reasons, from literature emerges the importance to consider the early sustainability aspects. Considering environmental, social and economic aspects right from the beginning and integrating these aspects in the product design is a possible approach for sustainable product development. However, it is crucial to provide optimal support for designers and engineers during these processes (Bocken et al, 2014).

3.1.2 Tools and methods framework

A large number of eco-design methods and tools that support the integration of sustainability consideration during the product development have been developed in the past years and extensive information about them are present in literature. Baumann et al. found in their literature review near 150 eco-tools (Baumann et al. 2002). Despite this great number, the use of eco-design methods and tools as industrial practice is still limited today (Lindahl, 2005).

This paragraph wants to classify the different existing methods and tools in order to determine advantages and drawbacks of various methods and tools. This deeper investigation has, also, the purpose to identify which methods and tools can be used as a starting point for the development of the eco-design methodology proposed in this work.

Some authors have already proposed a classification. For example, Baumann et al. classified eco-tools in six categories: frameworks, checklist and guidelines, rating and ranking tools, analytical tools, software and expert systems and organizing tools (Baumann et al. 2002). Knight and Jenkins, for instance, chose only three categories: guidelines, checklists and analytical tools to draw a simpler classification (Knight and Jenkins, 2009).

Rossi et al., identified and clustered these tools and methods into eights groups, these include qualitative rules of thumb and checklists, semi-qualitative approaches and purely quantitative impact assessment and optimization tools (Rossi et al.,2016).

These groups are:

- LCA tools;
- CAD integrated tools and methodology;
- Diagram tools;
- Checklists and guidelines;
- Design for X approaches;
- Methods for supporting the company’s eco-design implementation and generation of eco innovation;
- Methods focused on the product development process;
- Methods for integrating different tools;

The proposed list established for the examined eco-design tools and methods follows this last classification and tried to focus on that which are related to the assessment and the design of mechatronic products.

LCA tools

LCA is the most popular tool used for eco-design and is a framework which provides quantitative data on product environmental impact along its complete lifecycle: from cradle (the extraction and production of material) to grave (the End-of-Life). The final result of an LCA analysis is an assessment of all the environmental impacts related to the current product design and lifecycle (Westkämper et al., 2000).
LCA is one of the most mature tools for eco-design. It has been formalized in the ISO series 14000 and has been implemented in various software tools in order to simplify it use for the industry and policy makers.
According to ISO 14040 (ISO, 2006), an LCA study is divided into four phases (Figure):

- goal and scope definition phase: define the product, process or activity, establishing the system boundaries.
- lifecycle inventory analysis phase (LCI) comprises the compilation and quantification of the inputs and outputs for all processes related to the lifecycle of the product under analysis.
- impact assessment phase (LCIA): calculates the ecological effects of energy, water and material usage.
- interpretation phase: evaluates the results coming from the assessment analysis.

Several tools based on LCA analysis exist and most of them are commercial software such as GaBi and SimaPro. These tools are applicable in a variety of sectors thanks to comprehensive databases. Increasing interest has been focused on OpenLCA which an open source tool is, which is flexible because of its flexible databases but requires a deep expertise.

Figure 10 - LCA framework and phases

Due to the difficulty to collect data to evaluate product’s environmental impacts with detailed LCA software tools, many simplified LCA (S-LCA) tools have been developed (Kaebernick et al., 2003).

By reducing the data and environmental impacts indicators necessary, the assessment can be realized sooner in the design process and with less data on product shape and lifecycle. The simplification helps the integration of different design actors into the assessment. However, simplification lowers the level of consensus among the scientific community and reducing the data input to the process also increases the level of uncertainty on the results of the environmental assessment.

Another solution to reduce the time and resources needed to assess the environmental impact of the product lifecycle is to restrict the assessment to one specific indicator of environmental issue. This restriction is called Streamlined LCA. Streamlined LCA keeps the philosophy of LCA by evaluating product lifecycle but restricting the data to process to one environmental impact (Curran and Young, 1996).

The most common Streamlined LCAs used are related to climate change, such as the carbon footprint and global environment degradation (e.g. the environmental footprint (Finkbeiner, 2009).

CAD integrated tools and methodology

As presented by Rossi et al (2016), in literature there are many environmental analysis tools integrated with CAD system. This integration takes place by the necessity to directly evaluate the consequences of a design choice. The Data from the CAD models can feed directly the Life cycle inventory phase of an LCA assessment.

Gaha et all. (2011), proposed an integration CAD/LCA through a specific geometric database containing the environmental impacts of all of the product design technical solutions. Marosky (2007), who presented an algorithm allowing reciprocal data transfer between CAD (SolidEdge) and an LCA tool (SimaPro). Literature also shows tool prototypes which aim to extract information from the product's CAD model to evaluate its environmental impacts. For example, Cappelli et al (2006), is based on the product retirement information from the tree CAD structure. Analysing commercial tools available in the market, SolidWorks sustainability (Solidworks sustainability, 2013) is a CAD integrated analysis tool that estimates the environmental impact of the product by retrieving data directly from the design assembly. Despite their good proposition, these tools present some limitations, because they are not enough to obtain detailed results, due to their simplifications and the limitation of their databases.

Diagram tools

Diagram tools or environmental matrix approaches propose a qualitative or semi-qualitative assessment which can be performed when detailed information of the product shape and life cycle is available.

These tools have the form of a matrix or a table to be filled in by intended users. Most of those approaches derive from LCA and can be regarded as somewhat of S-

LCA. Due to its relative simplicity, they have potential to be accepted by enterprise, especially by SMEs.

One of these tools is the MECO matrix, which developed by Wenzel et al. (1997) and estimates the simplified environmental impact of each life cycle stage by calculating materials, energy, chemicals and other substances involved in the product life cycle. Materials and energy are calculated as consumption of resources. Chemicals are calculated according to a specific classification proposed in the method. Environmental impacts that do not fit into the other categories are included in the category called “others”.

The MECO Matrix is very useful to assess design alternatives, providing information on toxic substances and is easy to use compared to full LCA. However, designer may have some difficulties to fill it in without the help of an expert even though it is more designer friendly as compared with LCA. Furthermore, even if the required data are not intensive, it is difficult to establish them in the early design phase in case of a product development.

Another example is the METmatrix approach (Materials, Energy, Toxicity), developed by Brezet and Van Hemel (1997) which performs the analysis completing a table in which the rows correspond to the product life cycle phases and the column correspond to the material, energy and waste used or produced by the product. The rows correspond to the five different product life-cycle stages and the columns correspond to three important environmental issues: the material used; the energy used; and waste, including toxic emissions. The ERPA Matrix (Environmentally Responsible Product Assessment) proposed by Graedel and Allenby (2010) to estimate a product’s potential for improvements in environmental performance. Each lifecycle stage (pre-manufacturing, product manufacture, product delivery, product use, refurbishment, recycling, disposal) is evaluated with five criteria (material choice, energy use, solid residues, liquid residues, gaseous residues). The environmental impact for each of the lifecycle stages is estimated by grading each criterion from 0 (highest impact) to 4 (lowest impact). The tool generates a quantitative result (from 0 to 100), but no quantitative data are needed to perform the grading. The grading here is still very subjective and, as for the first two approaches, there is no weighting depending on the lifecycle phases. The ERPA matrix considers phases of the product life cycle, and it was not able to provide information about the product concepts in the early design phase that would consider environmental performances in different life cycle phases. These tools are very simple, but they provide only a qualitative results and general evaluations and they can be used only for a preliminary environmental evaluation.

Checklists and guidelines

Eco-design guidelines are the most basic tool used for a quick evaluation of the product’s environmental profile and help the designers to achieve a more environmentally friendly design. They are used to prioritize eco-design objectives by providing a set of general rules and their application is particularly useful during the first design phases. Qualitative methods and tool are used in the early design stages when there is a less data about the product. The goal is to provide information necessary to improve product regarding eco performances early in the design process avoiding design changes in the later stages of the product development. Guidelines are prescriptive eco-design methods and tool, checklists are comparative tool.

Many guidelines can be retrieved from literature and due to their level of generality, they can be applied to many different products and are too general to be used for Eco evaluation purposes. The most famous rules about eco-design are Ten Golden Rules by Luttropp and Lagersted (2006) which is a set of prescriptive guidelines and represent the most significant example of this typology of design rules. This approach is based on the summary of many rules that can be found in companies’ guidelines and in numerous handbooks.

According to Janin (Janin, 2000), checklists are usually formed as a set of questions that concern issues of environmental performance and functional aspects of the product. The list has been established based on the experience and doesn’t necessarily take into account the whole lifecycle of the product.

Among checklist tools, there is The Fast Five of Philips developed by Meinders (1997) used in order to evaluate and compare different product concepts with a reference product. In this checklist a list of question has to be answered clustered in 5 criteria categories: energy, recyclability, the presence of dangerous material, sustainability and reparability, service. The advantage of this checklist is the adaptability to different design situations because it was developed from the experience accumulated during the development of the precedent product. The disadvantage of this is that the results are more or less subjective and difficult to use.

Design for X approaches

Among qualitative tools, Design for X approach was developed to optimize specific product requirements, with the objective to satisfy a specific request to reach customer or stakeholder’s satisfaction, such as safety, reliability, serviceability, recyclability, disassembly, maintainability, etc.

DFX mainly aims to improve the specific target it wants to maximize but ignores all the other aspects of product lifecycle (Kuo et al.,2001).

For example, it possible to identify several Design for X approaches, such as Design for manufacturing and Assembly (Boothroyd et al, 2002), Design for Serviceability (Gershenson and Ishii, 1991), Design for Reliability (Rao, 1992), Design for Disassembly (Dewhurst, 1993)(Huisman et al. (2003), Güngeor (2006) and Cerdan et al. (2009), Design for Variety (Martin and Ishii, 2000) Design for product retirement and Recovery (Gungor and Gupta,1999) Design for Marketability (Zaccai 1994), Design for Environment (Haushild et al, 2004), design for Sustainability (Jawahir et al. 2005), Design for remanufacturing (Sundin (2004) Hatcher et al. (2011)

During last years, there is also the development of Design for Energy Efficiency and with the aim to correctly calculate the environmental impact related to the use phase, especially for energy using components, Domingo et al. (2013) proposed a scenario model to include all of the events that can or will occur during the use of the product by a generic user.

Methods for supporting the company's eco-design implementation and generation of eco innovation

Literary shows that it is still not clear to companies how to manage the integration of eco-design into the design process and into business process. Environmental sustainability represents a relative new aspect.

In fact, there is a need of organization on how to achieve the environmental goals pursuing continuous improvement of products.

There are many approaches for eco-design integration and some of them can be identified in literature since last decades. Shelton (1995) defines five stages for eco-design implementation considering different organizational characteristics and requirements. De Caluwe (2004) develops a maturity grid to measure the performance on the implementation of an eco-design procedure into the product creation process. McAloone (1998) proposes a three-stage model to represent the complex organizational changes that companies go through when implementing eco-design. Murillo-Luna et al. (2011) define four proactivity levels of strategic environmental behaviours and provide a list of environmental practices associated with each level. These methods have a managerial perspective and define a set of steps that companies should follow, in order to successfully implement and manage eco-design, but do not provide support to companies in the identification of the current profile in eco-design application. These proposals are overcome by the eco-design maturity model of Pigosso et al (2013) which aims to propose a management framework that enables company in the assessment of their current eco-design maturity profile with a comprehensive systematization of eco-design practices.

Methods focused on the product development process

The future environmental behaviour of a product is influenced by all phases of the design process and for this reason the simultaneous consideration of several specifications to support strategies has been investigated by several authors.

Platcheck et al. propose a methodology of eco-design for the development of sustainable

electric/electronic equipments (Platcheck et al. 2008).

Here, the design process and then methodology is divided into four phases: briefing phase, development phase, projectation phase and communication phase. The briefing phase places the project in its context and defines a framework. The development phase draws up an analysis of the situation in seven stages. During the projectation phase alternatives and technical draws of the final solution are created. The last phase refers to the communication part. Gurauskiene and Varzinskas (2006), Fargnoli and Kimura (2007), and Platcheck et al. (2008)

offered methodologies encompassing the whole product design process. Other methodologies focusing on one aspect were developed, for instance, the Life Cycle Planning, LCP methodology (Kobayashi 2006).

Gyi et al. (2006) suggested evaluation based on simulations, prototyping and testing of the product usability and the relative user behaviour to improve effective strategies to develop environmental oriented use products. The early design phase of the product development process is very important concerning the environmental issue because significant environmental decisions are taken in the prespecification phase of design (Bhamra et al. 1999). Kobayashi has developed a product life cycle planning (LCP) methodology in order to integrate quality, cost, and environmental aspects simultaneously in the early design phase (Kobayashi 2006). The author adds to this methodology a systematic approach to eco-innovative product design consisting of idea generation using TRIZ, design uncertainty evaluation and an eco-efficiency indicator.

In relation to the use phase consumption monitoring and evaluation, Domingo et al. (2011) presented a methodology based on the calculation of an indicator that enables a design team to drive energy efficiency more effectively during the design process.

All those different methodologies highlight important eco-design activities, but they do not provide specific tools to support the design process.

Methods based on integration of existing tool or development of new tools

Literary analysis shows that many methods have been developed to integrate existing ecodesign tools in company activities to approach to sustainability dimension or have been developed with new specific tools.

Here are presented three methodologies based on the integration of different tools:

Dufrene et al. (2013) presented the G.EN.ESI methodology for eco designing manufactured products, showing that integrated design is a key element for the success of eco-design projects. Yang and Chen (2011) proposed an approach that integrates the Case Based Reasoning (CBR) and TRIZ methods. CBR can obtain the desired functional characteristics of a new design in an efficient way, and the TRIZ method ensures that designers can easily achieve design objectives due to the techniques provided by different technology fields.

Sakao (2007) proposed a design methodology to support environmentally consciousness design of products by the integration of three tools: LCA, QFDE (Quality Function Deployment for Environment), and TRIZ. Russo et al (2018) proposed a methodology to integrate virtual prototyping into traditional design process in order to evaluate the use phase of energy related products in an environmental perspective.

Fargnoli and Kimura consider also the use of the most common eco-design tools inside the design process, as well as the integration with recent environmental regulations (Fargnoli & Kimura 2007). Indeed, they define an easy-to-use design process' scheme made up of a series of activities, which supply explanations on the use of some eco-design tools and on the application of the regulations.

Other authors focused on the development of specific tools

Rossi et al (2015) proposed a CBR methodology and relative tool in order to support designers in the implementation of eco-design strategies, by collecting and making available guidelines and company eco-knowledge in a structured Database (DB).

Domingo et al. (2011) developed the Synergico methodology which aims to help designers to better consider the energy consumption of electrical and electronic equipment during its design and to facilitate the integration of this criterion as any other design criteria (Domingo, Evrard, et al. 2011). The methodology is based on three tools, namely the in-use energy consumption tool (IUE), the guidelines, and the lifecycle check tool. Guidelines can then be used to obtain a list of strategies in order to converge towards an objective. Synergico includes a simplified lifecycle check tool which performs a very simplified LCA aimed at helping designers to take the best decision, but it cannot replace a full LCA according to the ISO 14040 standard.

3.1.3 Discussion

Different types of methodologies and tools have been reviewed and a separation between the two groups is not so obvious, because some of the methodologies focused on design activities include also some tasks related to the management and on the integration of different tools. An important point highlighted in this review is that eco-design aspects really need to be integrated into the design process.

The implementation of methods and tool is the primary action, but the developed solutions are usually too far from the needs and features of industrial context. The academic research provides detailed methodologies often too complicated to be applied in daily industrial activities. On the other hand, industrial realities are looking for simple and robust tools which aim to facilitate the decision-making process concretely since the early design phase.

Quantitative tools (e.g. LCA) allows the assessment of product environmental performance along the entire life cycle but require a high level of information and details (data, time, experts) (Michelin et al. 2014; Millet et al., 2007), and often are quite complex. In addition to this the selection of the most appropriated tool for the company requirements is very difficult and can be difficult to utilise the results of a tool to actually inform decisions during the design process.

In these tools and methodologies, often there is little or no indication on the users supposed to used them and more broadly on who is supposed to do what and when in the product design process. Moreover, some methodologies recommend specific types of tools or even proposed their own tools but none of them bring a solution to support and facilitate the collection and the management of environmental data and information at every step of the methodology and the connection with traditional design tools.

As a result, those methods and tools are scarcely applied within industrial context. To conclude, the following barriers can be identified:

i. methods complexity;
ii. involvement of specialized personnel;
iii. timing and high resources required;
iv. lack of concrete guidelines and supporting tools;
v. hard integration within the product development process;
vi. prioritizing in projects and objectives.

To facilitates the eco-design integration in the product design process, from this literary review is important to highlight some important needs:

- Definition of specific action in the process design;
- Definition of different steps to realize for a good implementation of eco-design;
- Development of more simple quantitative tools to carry out the actions and facilitate environmental perspective;

On the other hand, diagram tools and checklist can be a good vehicle to introduce environmental aspect in company departments, but their efforts can result useless without previous knowledge. In fact, these tools are not able to provide a significant environmental evaluation. The environmental suggestions provided by checklist and guidelines can be useful only for environmental experts which can understand the strategy to implement.

Another important aspect is the integration of eco-design in the product development process focusing on the management of eco-design activities. Companies find difficulties to integrate sustainability aspect into early stages of product development because their existing processes are less formal in these early stages (Mougenot et al.,2008).

This difficulty is due to the lack of company of a systematic approach that is required to achieve environmental goals and maintain a continuous improvement within the product design process (Boks and Stevels, 2007; Marimon et al, 2011).

The pursuing of environmental goals requires time and resources and often companies don’t provide additional time or additional resources to design teams. (Bey et al, 2013).

3.2 Knowledge sharing and eco-knowledge: issues and challenges

3.2.1 Knowledge sharing tool in companies

The literary analysis was realized with the aim to investigate the concrete knowledge and awareness of environmental sustainability issues, as well as the concrete issues that currently limit the application of eco-design in design departments of Italian manufacturer companies. The survey (Favi et al., 2017) showed that interviewed companies identified some problems, which limit their daily work. The principal and more common identified problems were “scarce collaboration, poor communication and inefficient organization and data sharing”, thus underling how the design process could be improved if an effective cooperation among the actors and the departments of companies will be fulfilled.

Design activities are strongly depending on knowledge, which can be defined as the sum of individual designers’ education and company experience, reached on a specific product or family of products and used to design, develop and innovate them. The knowledge is recognized as a crucial element for the survival of industrial organizations (Asrar-ul-Haq and Anwar, 2016) and its sharing among different actors of the design process as an element for the success of the organization (Witherspoon et al., 2013). Knowledge sharing can be defined as the transference of knowledge among individuals, groups, teams, departments, and organizations (Crossan et al. 1999 and Ipe, 2003).

The reuse of knowledge is particularly useful for companies, which operates in mature domains, due to the high quality of knowledge they are able to produce, the overlapping of new versions with the previous ones and the possibility to dedicate more time to innovations (Baxter et al., 2008). Furthermore, observations of engineering designers found that approximately 24% of a designer’s time is spent in identifying, acquiring and providing information (Marsh, 1997). Companies in fact capture a lot of information related to their products and usually they store them into repositories; however, a complete understanding of how to effectively reuse these data and turn them into a factor of competitive advantage is still needed (Ahmed and Vianello, 2009).

Focusing the attention on sharing approaches, several works have been realized both in academic and commercial fields. Among the academic ones, all these approaches and tools usually allow improving the design process by the consultation of data, but they are not able to effectively share the tacit knowledge (Mehtzer et al., 2005). Some of them have the aim to preserve people knowledge, with reasons, which vary from end of careers to the natural turnover (Briggs et al., 2006) (Chevalier et al., 2013).

However, these tools are often not customized for the specific company, and contain general data or results of pilot projects, which is owned by companies and in particular by those employees with high experience. If commercial tools are analysed, the classical management systems usually allow to collect in a unique repository all the documents a company have, without allowing a smart classification of the information that are contained inside those documents, if we exclude a univocal codification of file names. This fact, if from one side, facilitate the retrieval of documents for the users, do not guarantee the effective sharing and retrieval of company knowledge, due to the fact the user needs to know a priori what he is searching for. Other tools exist (Rossi et al., 2016), which support companies in the sharing of knowledge among departments, by inserting in a unique and organized repository all the data of past project. But they usually provide only a repository where storing documents, without providing a method to store in a smart way the knowledge (tacit and explicit) people have. As a consequence, they allow to increase the knowledge organization and to facilitate its storing, but not its useful sharing and effective re-using.

3.2.2 Eco-design and knowledge: a new challenge

If the case of eco-design is analysed, the situation becomes more complex. In fact, in this case, preliminary problems arise: company usually does not dispose of knowledge to share, due to the scarcity of implementation of eco-design approaches in industrial sectors and sometimes they have no competences and skills on environmental sustainability. Environmental sustainability represents in fact a relatively new aspect that companies start to implement in these last decades and for which much of the knowledge still has to be created (Baouch et al., 2014). For this reason, if the knowledge exists, it is often produced by external consultants and company's designers do not dispose of the adequate knowledge to interpret and correctly use it. But, as (Baouch et., 2014) observes, if the knowledge plays a key role 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.

Starting from these states, i.e. companies usually do not dispose of knowledge on eco-design, the analysis of the literature shows that several tools and approaches have been developed to collect general environmental knowledge. Among them, Russo et al. (Russo et al., 2011) proposed an approach based on the integration of Life Cycle Assessment (LCA) and TRIZ eco-guidelines, with the aim of supporting the implementation of the eco-design approach in small and medium European enterprises. Garcia-Diéguez et al. (Gracia-Dieguez et al., 2016) developed a more complex framework to integrate the criteria provided by quantitative environmental indicators on the basis of Fuzzy Preference Programming method features and fuzzy logic reasoning. Teulon and Canaguier (Teulon and Canaguier, 2012) proposed a web tool called the "Seeds4Green", that provides environmental contents such as LCA studies, EPD, green-purchasing guides, to everyone who is interested with these topics. Anyway, the majority of these studies are older than ten years and therefore useful to have a general panorama of the environmental situation of a product and not easily to be translated by companies into specific choices for the products they develop.

3.2.3 Discussion

Some important points and ideas have been highlighted from this review.

The introduction of eco-design requires a large amount of knowledge in different fields, such as the design team and the other departments (marketing, production, purchasing). Currently, many companies lack the necessary environmental knowledge to support eco-design activities (Ilgin and Gupta,2010). From this literary analysis emerged that companies need knowledge to implement eco-design as well as also the necessity to acquire data to support the eco-design activities and to integrate a new expert in the design team. Many approaches and tools allow improving knowledge, but they are not able to effectively share and collect it during the design process. To overcome the limit, there is the need of a methodology and tool to support designers in the implementation of eco-design strategies, by collecting and making available knowledge in each phase of the process design. This knowledge allows to facilitate the problem solving and to standardize the design/redesign process. In addition, the collection of knowledge allows to train companies in learning to acquire competences on the sustainability issues and to guide young inexpert designers during their first design activities, through the sharing of tacit company eco-knowledge and practices about past projects. All challenges in the knowledge concerns different themes such as the necessity of a large amount of knowledge developed both within the design departments and the other ones, the difficult to find the environmental impact data required for the eco-design, the necessity of expertise in the eco-design implementation. These challenges highlight the necessity to find a way to store knowledge in order to capitalize and to make it available for future projects. Designers will increase their eco-knowledge on their activities during each design project, so they could then consult these data in future, and they gain experience and become more and more comfortable with eco-design topics.

3.3 Environmental aspects into design and development of energy-related products

3.3.1 Performances of products in compliance with eco-design requirements

Household appliances represent 25% of European energy consumption (EEA, 2013). The energy efficiency of major household appliances continually increases, and some researchers estimate energy savings of over 10% by 2020 (Laicane et al., 2015). The EU 20-20-20 Energy and Climate Package aims to improve the energy efficiency in all sectors by 20% by 2020 with a 20% reduction in consumption. Part of this savings can be achieved by changing consumer awareness, habits, and routines. However, it is very important to reduce the purchase of products with low efficiency and high energy consumption in terms of electricity, water, fuel, etc.

The energy efficiency and the general reduction of energy consumption are considered as key means for reducing greenhouse gas emissions (GHGs) (Gillingham et al., 2009).

Wang et al. showed that environmental awareness, social interaction and resident educational levels have significant effects on purchase intentions (Wang et al., 2017).

The EU Commission (EC) has been regulating the requirements regarding the energy efficiency for different energy consuming products, such as several household appliances (Gynther et al. 2012). In this context, the first European milestone was the delivery of the EU Ecodesign Directive (Directive 2009/125/EC), which establishes a framework for setting mandatory ecological requirements for energy-using (EuP) and energy-related products (ErP) sold in all Member States (Gynther et al., 2012).

European Directive 2009/125/EC establishes the eco-design requirements related to domestic and commercial kitchen appliances typically used in household appliances such as cookers, hobs, grills, and electrical mains-operated domestic range hoods. The European regulation (EU) No 65/2014 and in particular the European Standard EN 60350-2 “Household electric cooking appliances – Part2 – Hobs: Methods for measuring performances” regulate the measurement of energy performances of induction hobs. In the environmental impact assessment of a product, energy efficiency aspects play an important role in the choice between different product alternative, the subsequent behavior of the consumer in use phase of a product, and consequently in the decision of how to dispose the product at the end of use phase.

Measuring performance, mainly temperature dependence, for electric cooking ranges, hobs, ovens and grills for household use is a crucial parameter for producer perspective because represent a powerful selling point. Accurate measurements of cooking appliance performance are essential to help the industry to produce more energy efficient appliances. The standard 60350-2: 2011 specifies necessary methods for measuring performance, heat distribution and energy consumption.

Regarding the environmental aspect of the product and the lifecycle, the use phase is the most contributing aspects for some products, especially for the household appliances, so a robust modelling of this stage is fundamental (Germani et al., 2015).

During the last years, the manufacturing industries have been completely rethinking their way of designing and manufacturing by implementing responsible strategies which are focused on products that have an ecological, social, and economic value. Eco-design is an approach that puts evidence on the environmental aspects of a product, during the design and development stages, with the goal of minimizing the environmental impact (IEC, 2009). The important aspect of the eco-design is the combination of the process engineering product design procedures with the consideration of environmental aspects. The development of a product has to satisfy criteria such as price, performance, quality, and in an eco-design approach, these aspects can be also focused on the environmental requirements (Wimmer et al., 2010) (Fiksel et al., 1996). Energy efficiency has a significant environmental aspect, and the employment of more efficient energy consuming products could lead to a reduction in the total amount of the global energy consumed.

The environmental gains related to Eco-design and energy efficiency actions are clear in terms of social impact (Tyl et al., 2014), but few studies are going to analyse the cost impact on the market to understand if the energy efficiency products are economically efficient or not. Household failure to minimize the total costs of energy-consuming investments has become known as the “energy efficiency gap.” (Carrol et al., 2015). The delivery of energy efficient products requires the development of prototypes. Possible approaches can be bottom-up or top-down. A bottom-up approach is expensive and time-consuming and requires detailed manufacturing information (Kengpol et al., 2011). In fact, this first approach is similar to developing a new platform for products. A top-down approach is less expensive than the first. This second approach focuses on study of the best solutions in terms of cost and energy efficiency (Kengpol et al., 2011) to support the decision-making process before starting the design process. Generally, configurator tools can support a top-down design process in several applications, from assembled-to-order products to engineered-to-order ones. The household appliances industry represents a case in which a family of products can include hundreds of codes (Malatesta et al., 2015). Each code is a variant of a product, and its design can start from the study of a similar configuration. A top-down design approach, which uses configuration tools, can reduce time and costs related to the design phase and enhance the re-use of past configurations (Malatesta et al., 2015). Some researchers have found that consumer willingness to pay a price for high-efficiency products depends on the back premium related to the energy savings (Zhou et al., 2016) (Galarraga et al., 2011).

Generally, the energy money savings is a common metric from the consumer’s point of view for comparing the purchase of an energy-consuming product.

However, the price of energy does not reflect the true marginal social cost of the energy consumption. In fact, the cost due to all the environmental externalities associated with the production and consumption of energy is very difficult to estimate and is not included in the purchasing energy prices. A recent study showed that Chinese consumers are very conscious of electricity savings. They consider energy-savings an important factor when selecting appliances (Zeng et al. 2012).

This study also showed that Chinese consumers are only willing to pay less than 10% more for energy-efficient appliances. China, which is the world's largest producer and consumer of household appliances, has been developing and implementing energy efficiency standards and labels since 1989 for a wide range of domestic, commercial, and select industrial equipment (Zeng et al. 2014). Because of current EU policies, in Europe, several ErP and EuP come with an energy label that describes the energy efficiency using an Energy Efficiency Index (EEI). Because the energy labelling leads consumers to invest in energy-efficient products, OEMs and manufacturers must completely rethink their methods of designing, manufacturing and consuming by implementing a responsible innovation strategy (Tyl et al, 2014).

The pursuit of more energy-efficient products introduces an additional cost and time in the design of every OEM involved. To reduce the time and cost impacts for the delivery of more efficient products, big OEMs have been investing in Eco-innovation activities since the delivery of the Ecodesign Directive (Kengpol et al. 2011). This situation has enhanced the adoption of "Design for Environment" and "Ecodesign" studies in design processes (Kengpol et al., 2011). As established by ISO 14062:2011, the Ecodesign approach, which is defined as the integration of the environmental constraints in the development process of product design, leads to two types of analysis: Life Cycle Assessment (LCA) and Design for Environments (DfE). The same standard defines "Eco-innovation" as a collection of actions that reduce the environmental impacts of a product. Several research studies show real difficulty in making clear the differences and similarities between Ecodesign and eco-innovation (Cluzel et al., 2014), as well as defining a boundary between the two concepts (Tyl et al., 2010).

Sherwin underlines that a current Eco-design approach is focused on preliminary studies such as LCA, which do not involve a functional analysis of the product (Sherwin et al, 2004). In fact, there is a lack of tools that support the eco-innovation process considering different views of the product, including its functionalities and performance (Jones et al., 2003). As a solution, Eco-design tools should interact with the early phases of the product configuration related to household appliances (Cicconi et al., 2016). Malatesta et al. proposed a matrix-based method to configure new variants of household appliances eliciting the requirement compatibilities from existing products (Malatesta et al., 2015). This approach describes how to support the configuration of cookers and provide feedback regarding their cost and technical feasibility; however, they did not consider the calculation of product performance and efficiency. Kengpol and Boonkanit presented a design methodology to support the entire decision-making process in eco product design and re-design from an Ecodesign point of view (Kengpol et al., 2011).

They proposed a calculation model for determining an Ecodesign concept indicator. However, their approach did not consider the use of configuration design and simulation analyses to predict a reliable value of the product EEI. An introduction research analysis addresses the possibility of combining configuration features with the calculation of product performance and efficiency (Cicconi et al., 2016).

Focusing on the design of household appliances, an early simulation analysis can be suitable for supporting activities such as product development planning and decision-making.

Currently, there are no commercial software tools or research studies that can concurrently support the engineer in the product configuration, the energy evaluations of ErP, such as household appliances. The product engineering needs innovative, functional, and rapid design methodologies to have a more energy-aware product design in accordance with the recent legislation.

During the last years, many researchers have focused on household appliances energy efficiency, in fact past research has shown how the use phase of household appliances has the strongest environmental impact compared with the manufacturing phase. Bevilacqua et al. showed how to reduce the environmental impacts of a cooker hood by approximately 36% via the replacement of the single-phase electrical motors with an inverter-drive three-phase induction one and the use of LED lighting (Bevilacqua et al. 2010).

A great number of research works have been carried out, and most of these works are focused on the increase of energy efficiency, reduction of manufacturing, and use costs (Acero et al, 2013) (Zhang et al, 2004).

Some authors have studied the behavior of cooking stoves and pots with theoretical models and experimentation, and in particular case, the thermal efficiency of pots was calculated and measured (Cicconi et al., 2016) Other researchers have focused on the efficiency improvement of the cooking processes by means of the pot optimization. In the other papers, a study of the efficiency of pots through experimental and neural network method is presented. Other works have focused on models that consider a uniform distribution in the bottom of the pot (Landi et al., 2016).

These works needed physical prototypes, and their study is not focused on a product based on Eco-design Directive since its early design. Against this background, it is important to employ design tools and methods able to support the designer in the early estimation of the product energy performances using virtual prototyping tools.

However, the assessment of cooktops performances and therefore the evaluation of their actual improvement remain challenging, at the same time there is a lack of agreement about the methodologies employed for performance evaluations.

A tool for the simulation of cooktops operational phase based on thermodynamic modelling could provide additional information regarding the performance of cooking system. Literary analysis shows several works which developed thermodynamic models, but they are typically conceived as tools for the design and simulation of the technology, rather than for the simulation of performances. McCarthy and Bryden (McCarthy and Bryden, 2016) proposed a steady-state heat transfer model for the improvement of the cooking stoves, investigating fluids around the pot. The limit of this work is that the discussion is not extended to the thermodynamic phenomena within the pot and assumes that the water in pot is already at the boiling temperature. Similarly, other works developed detailed thermodynamic model including also losses from the pot sides and heat transferred to water volume, but in both case the water was assumed to be already at the boiling point (Gogoi et al., 2015) (Kshirsagar et al., 2015)

Other works have focused on this important aspect, with the development of a prototypical software tool in order to simulate the energy performances of a kitchen hood configurations or with the study of a model which is able to estimate the energy efficiency of the induction hobs during the operational phase (Cicconi et al., 2016)

From this literary analysis emerges that the existing models do not consider all the parameters that are needed to allow the simulation of the operative principle of the system under different conditions. A virtual model focused on the induction hob-pot system and on its different configurations, would be needed.

3.3.2 Discussion

From literature, has emerged that for the development of eco-driven products Eco-design tools are required to support eco-innovation and related sustainability improvements. This context requires the employment of design tools and methodologies able to support the designer in the early estimation of product performances using virtual prototyping tools.

there is the necessity that the engineers become more aware of the product performance and can compare different configuration cases during the early design phases.

Literary analysis show that the existing models do not consider all parameters that are needed to allow the simulations of performances and testing procedures in different conditions. Actually, there is a lack of commercial tools that provide interfaces for the configuration and simulations of products in order to make a designer more aware of the relation between the product configuration and the energy consumption in operational phase.

Virtual models focused on the system and its configurations would be needed. The idea underpinning this literary analysis is to extend, by means of simulations, the range of information about performances that can be provided based on test campaigns in fixed conditions. These days, the delivery of products that are compliant with higher energy efficiency requirements is very important and customers are increasingly aware and conscious of product energy efficiency and consumption, so it is necessary understanding, since the early phase of product design, if a given product can meet the habits and the necessities of users.

3.4 The support decision-making into sustainable product development

3.4.1 The support decision-making into design process

Engineering design is under increasing pressure to perform better in terms of environmental requirements, low-time production, high-quality materials that can provide competitive advantage for the organisation.

Decision analysis is the most important part for designers to choose among alternatives, based on the expected feature associated to each alternative and its consequent impact. Environmental aspects are not always the prioritized aspects of the traditional decision making. During years, many decision support systems are developed to guide designers towards the best decision. Cost benefit analysis (CBA) is an approach developed to identify the alternative that can achieve a precise goal with lowest cost (Mishan and Quah, 2007). In addition to CBA, there is the multi-criteria analysis (MCA) which is used to evaluate different alternatives based on a set of criteria. (Figueira et al., 2005).

These approaches are used in different sectors to help decision makers to choose the most appropriate alternative, but often the environmental issues are not considered. In fact, the best alternative according to CBA may not have the best environmental performance (Chester and Horvath, 2009).

A satisfactory product design should incorporate both physical performances, ecological, economic and social aspects.

The lack of a proper environmental impact assessment in decision analysis underline a difficult to understand the needs and the possible ways to integrate the environmental impacts into existing decision process.

The implementation of the sustainable development concepts requires the use of appropriate methods and tools in the product creation process. The product properties, which are defined during the product development process, should support and ensure environmental dimension throughout the product life cycle.

Researchers and designers developed many methods and tool to assess environmental impacts such as Life Cycle Assessment (LCA), Environmental Impact Assessment, input-output analysis.

LCA is currently the most mature with its basic principles based on international standards ISO 40040/14044 (Kloepffer, 2008). It quantifies resource use and environmental impacts that are associated with product or service and is a promising tool for assessing environmental sustainability.

It has been adopted in different sectors, both public and private in USA and UE (Bosso et al., 2012) but it is not a legal requirement in any regulatory context. LCA aims at assessing environmental impacts, it is not a conventional decision analysis tool. As a promising tool, LCA provides a mature and ISO standardized methodology to assess a full set of environmental impacts. However, the ability to be integrated in the common decision analysis tool such as CBA presents still challenges, due to the lack of common scopes and purpose, and methodological differences (Moller et al., 2013) (Huang et al., 2017).

Some authors highlight that CBA has been mainly applied for policy or strategic decision making, where the main focus was the project and put emphasis on the socio-economic impacts rather than external environmental impacts. In contrast, LCA is product oriented because focuses on environmental impacts rather than social and economic impacts. In recent years, LCA has been used in a broader scope, such as assessing impacts for services (Barjoveanu et al., 2014), urban metabolism (Goldstein et al., 2013), larger scale applications (Lotteau et al., 2015) and territorial planning (Loiseau et al., 2018). These works highlight the difficulty to apply LCA analysis or CBA approach since the early phase of product design. For obtaining a sustainable lifecycle for a product, it important that the decision making should occur in the early phase of the design process. However, the early phases contain multiple uncertainty in describing the design and it’s very difficult to make decisions focused on sustainable product creation. Wood and Antonsson (Wood and Antonsson, 1989) proposed a fuzzy set-based approach, called the imprecision method, for manipulating imprecise design information through the specification of preferences regarding the design and performance variables.

An important support to the decision making in the product development is also the retrieving of knowledge through intelligent systems and case-based reasoning (CBR). Knowledge based design also represents a valid support to the product design (Leake et al, 2001) (Roller et al., 2003).

CBR simulates the approach how humans solve problems: using the solutions of similar past problems to solve the new ones and stores the successful cases in the case base. With the accumulation of new cases, the problem-solving ability of the CBR system improve continuously (Hammond, 1990) (Watson, 1994).

Literary analysis shows that different decision support techniques have been suggested and applied in environmental management (Huang et al., 2011; Gregory et al., 2012; Linkov and Moberg,2012). All of them structure the decision-making process into procedural steps and assess the degree by which decision alternatives fulfil the objectives. Some techniques rely on qualitative assessments, while others quantify preferences and predictions and rank alternatives based on scores of the expected fulfilment of objectives.

Although research shows an important increase of the environmental decision-making process, it is important to incorporate it during the product design process in order to support sustainable choices.

3.4.2 Discussion

The literary analysis emphasizes the importance of a solid foundation background of a decision support for environmental choices during the design process. This aspect is important to guide the environmental necessities into the decision making. The environmental dimension of the decision-making during the product design process have to be characterized by different elements such as transparency of procedure, a good representation of the objective to pursue, a good conceptual basis. This multiplicity of elements explains why decision support in environmental management during the design process is very difficult. To overcome this difficulty a deep knowledge is necessary and a well-structured method to support the decisions and the possibility to choose among different alternatives.

There is thus a clear need for a better assessment of environmental impacts to be incorporated into decision analysis in general and in particular into the design process in order to support sustainable system choices. A satisfying decision support procedure with a careful implementation can contribute significantly to the environmental decision making.

3.5 Detailed problematics and working hypothesis

This section aims to formulate the problematic form from the different analysis derived from the state-of-art realized in the previous sections.

The consideration of the environmental dimension in the design process starting from its definition and its principles met some challenges. Authors develop different methodologies and tools and concentrate their efforts on different aspects of the eco-design aspects.

The state of art enables to raise some issues and problematics which can be identified in four main themes:

- The integration of the environmental aspects into the product design process;
- The creation and the collection of a specific eco-knowledge to share and increase inside the company and to use as support for designers;
- The difficult to analyse the performances and use phase of products, in particular the energy related ones, in compliance with eco-design standards.
- The lack of valid support to designers into the decision-making process to evaluate environmental issues to choose the most satisfying alternatives possible.

Moreover, the review showed that there is not a complete solution but has allowed to list the necessary features, methodological as well practical, to build a global solution. Through the state of art, the aim of this work is to overcome all these problematics during the design process in order to remove them. The solution is to Transform these important lacks in point of strength of the methodology and satisfy them. The task is to consider the point of strength as function to be satisfied by the methodology and which characterize the approach.

Figure 11 synthetizes the research approach to build the proposal (presented in the Chapter 4)

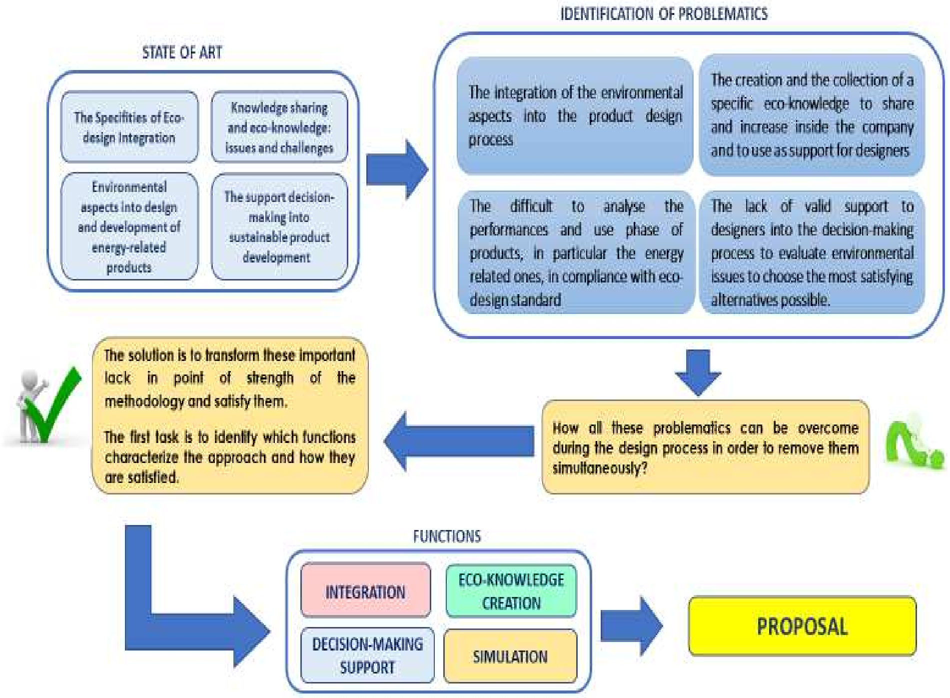


Figure 11 - Summary of the research approach to build the proposal

Chapter 4.

The proposal: A methodological approach to support development of sustainable products

4.1 The Virtual Eco-Design: the functions of the approach

The Virtual Eco-design approach (V.E. approach) has been conceived to integrate eco-design in the product development process.

The aim of the V.E. approach is to support engineers in ecological design choices during the early phase of product design, by collecting and making available guidelines and eco-knowledge in a structured database that integrates information related to eco-design and virtual prototyping.

The novelty in this approach is the association of virtual prototyping to environmental aspects during the product design process and the possibility to share knowledge using database among designers which are not involved into the environmental issue.

The aim of the approach is to develop a support to help new or experienced designers to consider the environmental issue in the design process.

The first task is to identify which functions characterized the approach and how they are satisfied. The functions of the approach that need to be investigated are the followings:

- ***Integration:*** the function of the integration of the environmental dimension in the product designer’s activities.
- ***Eco-Knowledge creation:*** the creation of a company knowledge that collects all the information in order to have guidelines for development of the new design concepts.

- ***Analysis of Performances***: the function of analysis of performances though the simulation of the energy performances and use phase in compliance with eco-design standard with the development of virtual models (one for each mechatronic product).
- ***Support decision-making process:*** The function to support the decision-making process to evaluate environmental issues and to choose the most satisfying alternative possible.

The database is the core of the V.E. approach, in fact, to better explain the methodology, it is possible to have a reference to the mathematical language:
"A function is defined by three elements: a domain X, a codomain Y and a law f(x) which links to each element x of the domain X, one and a only element of Y, indicated as f(x)." (Zwirner, 1990).

$$f: X \ \rightarrow Y$$
$$f: x \ \rightarrow f(x)$$

The set X (from where the function f "takes" its values) is the domain of the function f, while the set Y (where there are the values "returned" from the function f) is the codomain of the function f. The expressions "take a value" and "return a value" refer to a mechanical model of the functions, represented as a mechanism that, given it an element of the domain, "transform" it into the corresponding element of the codomain (Bacciotti, 1994).
In this methodology, the four functions "Integration, Eco-knowledge Creation, Analysis of Performances and Decision Making-Support" represent the laws which links the domain and the codomain. The domain of definition of these functions is represented by the V.E database, in which a set of "input" for which the functions are defined: these inputs are eco-design guidelines, virtual prototyping studies and lifecycle analysis which are stored and organized in order to facilitate their consultation. Instead, the codomain is represented by all possible "outputs" for

each member of the domain, which are possible design solution which satisfy functions.

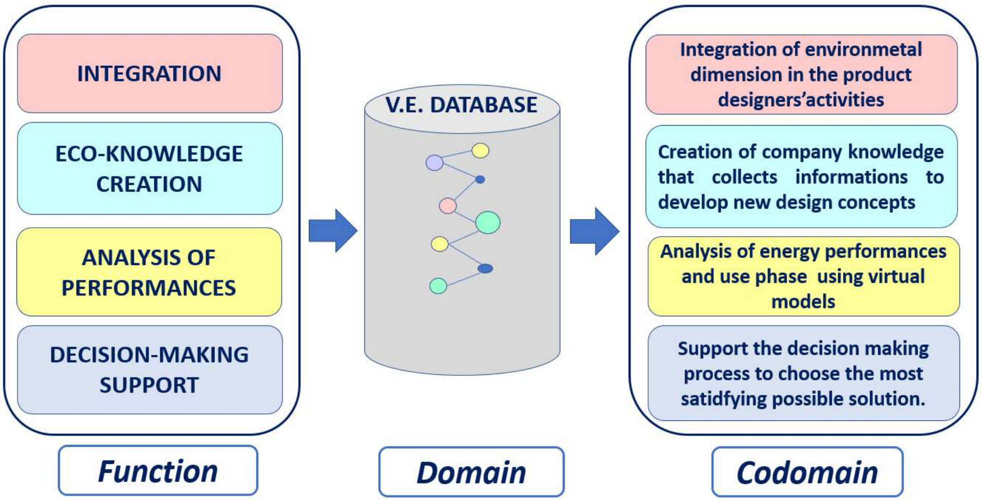


Figure 12 - The functions of the approach

Integration

The integration of environmental parameters into product design process is a need emerging from the literary review. This integration is particularly important during the prescriptive phase of the study. A product designer can choose particular features of the product without taking in account the environmental aspects (i.e. environmental parameter not integrated). The idea underpinning the V.E. approach is to integrate principles of eco-design standards such as laws, mathematical models, and thresholds in a virtual environment. The inputs derived from all the figures involved in the product design process can be satisfied in order to create a common strategy and to get the environmental achievements in the eco-design matters.

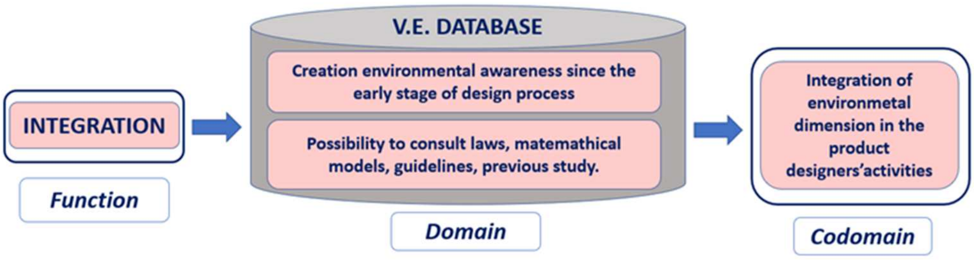


Figure 13 - Domain and codomain of the function "Integration"

The possibility for designers to consult indications coming from guidelines, as well as from previous design studies, organized for each step of the design process, creating environmental awareness and additional environmental knowledge, during the design process allows them to apply “eco-suggestions”, taking into account specific characteristics of the product under analysis since the early phase of design. Such characteristics way has an indirect effect on the environmental dimension that can be anticipated by this early stage integrated organisation.

Eco-Knowledge creation

The V.E. 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 environmental guidelines, all past choices made by designers during the design process and choices related to product/process data and simulations (materials, dimensions, strategies, etc.). The aim of the approach is to give to the designer to share experience, thus allowing both a easier transformation of individual project knowledge into common organisational knowledge and more easy access to company wide organisational knowledge. Currently, eco-knowledge is limited to mere supply of eco-design handbooks, guidelines lists. Designers stress that the handbooks mostly end up in a lost corner of faraway shelf, since the time for retrieving information is too high. Consequently, a flexible system directly connected with the product is necessary to be developed. In particular, in the V.E. approach knowledge is created starting from 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. In this way, the knowledge stored englobes the "common knowledge" represented by the knowledge that designers have matured thanks their experience and the "specific knowledge" maturated by designers during the implementation of eco-design practices. The sum of these contributes represent a priceless value for the company and its way to eco-design.

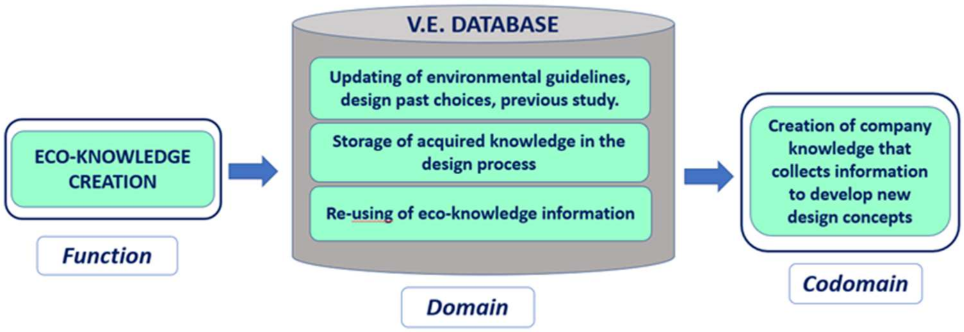


Figure 14 - Domain and codomain of the function "Eco-knowledge creation"

This methodology allows reusing eco-knowledge information for the development of new product or for product re-design. The content related to the eco-knowledge is strictly correlated to the intensity of the use of database by the designers.

As a consequence, at the first implementation of the tool inside a company, this section is empty, and it will grow day-by-day with the tool use. VE database is filled every time a new virtual simulation is performed and with LCA results of a new product. This information can be stored in the database and reused by designers during the environmental evaluation of the product during the design phase. In this way the information, on a case by case, will be more and more detailed.

Analysis of performances

The analysis of the energy performances and use phase in compliance with the eco-design standards is possible using virtual models.

The virtual prototyping is a numerical simulation of a virtual product model that can be analysed and tested from different aspects. In this case, through the virtual model is possible to analyse parameters linked to mechanical design (such as shape, material properties, mass, geometric dimensions, etc.) and operational parameters linked to use phase and performances of each specific product. Product virtualization allows the designers to evaluate the influence of new possible mechanical design solutions (such as shapes, dimensions, materials, etc.) on the use phase and to assess through the virtualization of energy label test their compliance to Directives. A simplified procedure needs to be developed with the aim to virtualize the energy label tests and to achieve robust results with a maximum of error estimated around 5% which can be considered acceptable for this kind of analysis, as literature shows (Cicconi et al., 2016) (Cicconi et al., 2017) (Landi et al., 2017).

By using virtual prototype and virtual tests, it is possible to speed the process by accelerating the tests loops. The virtual model aims to overcome the current issues for designers who develop mechatronic products (long trials, personnel costs, equipment, materials and limited number of tests). In this respect, the methodology involves the use of virtual prototyping techniques to recreate, in virtual environment, analysis that, otherwise, require experimental testing. The novel aspect of the introduction of the virtual model is the possibility to make more awareness the designer about their design choices, providing truthful results and not requiring long times of “preparation of the test”.

In this framework the virtual prototyping aims to support companies during the design phase, capable of implementing the eco-design directives, minimizing costs and time to market. The virtual model is able to virtually reproduce the specified performance of the product, decided in design specification of the product and established by product design team. The virtual model can be developed in order to reproduce the operational phase and the condition established by the test deriving from the regulation but also can be modelled in order to study performance of the product independently from the limits imposed by the regulation. This allows knowing the energy performances of the product since the early design phase without the necessity to build physical prototypes and explore the influence of the different design parameters on its operational phase.

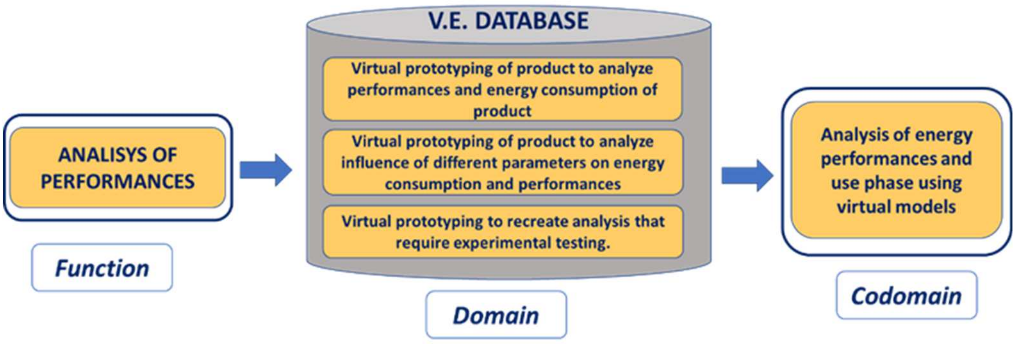


Figure 15 - Domain and codomain of the function "Analysis of performances"

Simplified CAD geometry of the system is required in order to include each level of product structure since the design process. Finite Element Analysis (FEA) and Computational Fluid Dynamics (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.

Through virtual analysis results, designers can identify the energy performances of products and which are the most influential parameters on product performance and consequently make the necessary adjustments since the early design phase.

Support decision-making process

The function of the decision-making process is one of the most important satisfied by methodology because preventive rather than corrective action should be taken as early as possible during the design phase in order to identify and reduce the environmental impact of product's whole life cycle. It is an important element when considering new product development. The V.E database will provide design rules, contextualized guidelines and analysis from previous study, and so the designers will be supported in their decisions more quickly. In the decision-making problems, designers need to define the problem under study, and they need to assess the risk of different objectives to reach with respect to different environmental attributes. The overall objective is obviously the selection of the best design compromise both form environmental point of view and performances aspect. The actual problem, however, is how the different design phases can be broken and integrated into eco-design principles. With the help of V.E database, this can be done more easily because in the early phases, the definition from the energy using products is adopted and following guidelines will be provided (such as raw material selections and use, manufacturing, installation and maintenance, usage, packaging, etc.) to perform more environmental design choices.

After, in the following phases, which are the most important phases, the previous choices will be identified and analysed in order to identify the main features of the product and eventually confirm or re-consider them (i.e. conceptual phase supported by virtual prototyping studies and LCA assessment). Defining the features of a product linked to the performances during the design phase in a decision-making process is very difficult. One reason is that environmental requirements can contrast with performances mandatory needs, so it needs an overview on a link between them. This role can be solved by the virtual prototyping studies, collected in the V.E. Database which can provide a support into the evaluation of different green product alternatives.

The regulatory pressure on designers has been increased and they need to short the development lead time by screening out various design options at the early design stage. In this way they can prioritize alternatives and select different design options for product in a timely manner. In fact, consulting previous virtual prototyping studies, designers can discard design options which are not compliant with the environmental and performance requirements claimed at this design juncture.

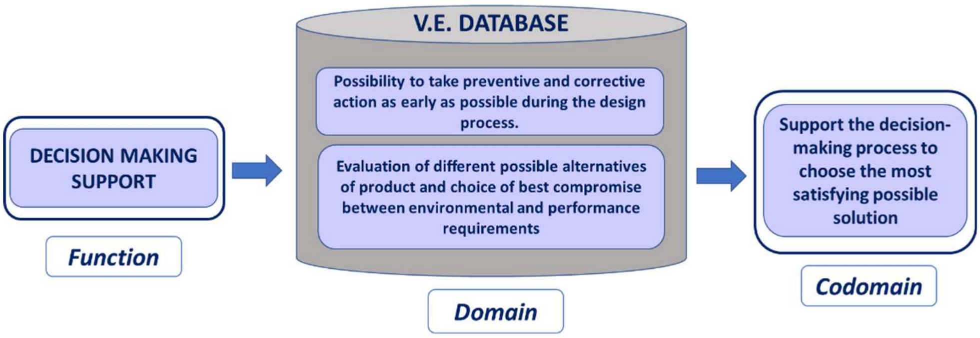


Figure 16 - Domain and codomain of the function "Decision-making support"

The complexity of these considerations has led to the conclusion that the first step for the development of the methodology is to clarify the objectives and the scopes of it. It is necessary the integration of the designers’ input and other figures involved in the design process in a unique product environmental strategy. In this way, since the early phase of product development, designers will be supported in the achievement of the environmental objectives expected for the product.

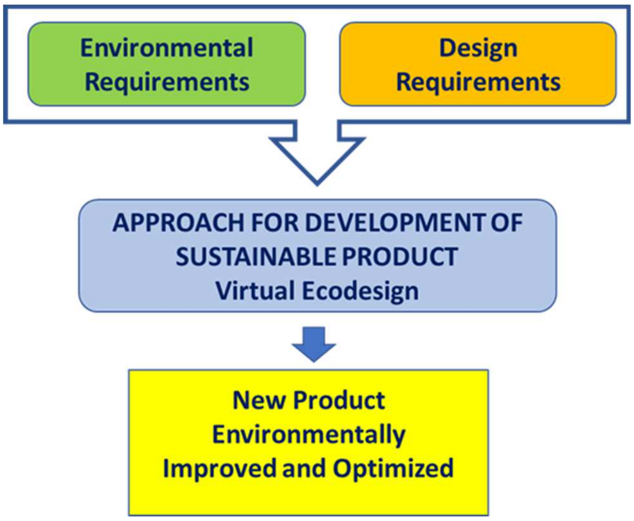


Figure 17 - Approach of the development of a sustainable product

4.2 The Virtual Eco-design within the Traditional Design Process

Every company has its own design process and even inside the same company the process can change to a product to another and the scheme represents basic steps to explain methodology into a classic design process context. Product development is a consolidated and standardized process in industries. In fact, this approach is developed into three main phases: initialization, main core and capitalization. These three phases include the design process steps, as described in the Figure 18:

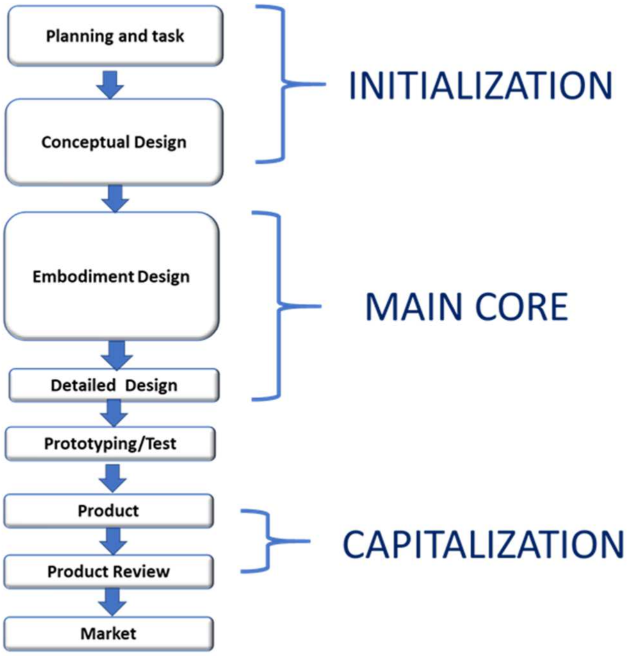


Figure 18 - Phases of the design phases

Design phases have a precise meaning and specific role in the overall process. With the aim of an efficient integration of V.E. within traditional design process, each step satisfies the function recognized in the previous section and is modified on the base of the proposed framework, as described here below in the Figure 19.

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 or to satisfy new requirements. A new design takes place in each phase of the design process with specific analysis, models and tools, as represented parallel the design process in the following figure and the role of the designer changes related to V.E. database for each step. The design project team consists of Designers, from the design office but also stakeholders from every department relevant for the project, mainly R&D, production, purchasing department, quality, etc. Designer is used as the universal term to refer to every stakeholder of the design team, regardless, of the department they come from.

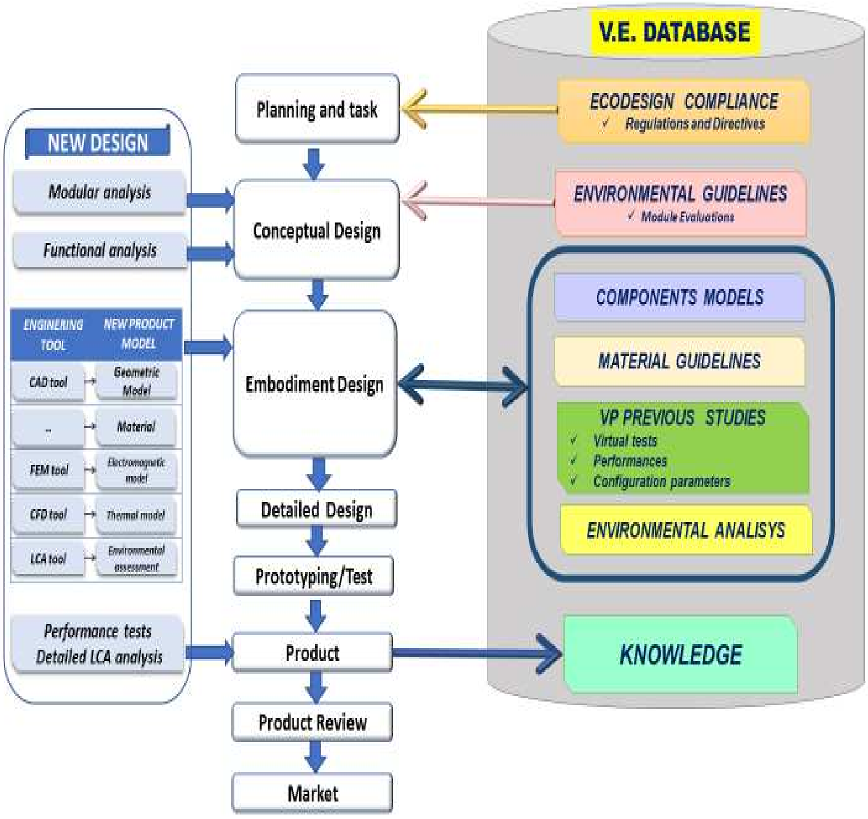


Figure 19 - The Virtual Eco-design Approach

Initialization

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.

The consultation of database can be an important additional element which offer to designers the possibility to reflect on specific product environmental characteristics and allows to consider the environmental aspects that could be more critical and difficult to solve in advanced phases of the product development process.

The designer consults the V.E. database not only if he doesn't know directives, regulations or guidelines, but also to improve his knowledge.

Conceptual Design. In the second step, the 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. The product is broken down in different modules/components with specific functions. During this step, only "high level" information is available by the consultation of VE database. So doing, designers can configure the product architecture combining "high level" eco-design suggestions and other traditional recommendation (e.g. costs).

The eco-design suggestions in this phase are a generalized set of guidelines that can be consulted as a synthesis of a number of environmental design guidelines. In this phase environmental information should be quick and easy to understand and designers can identify the main environmental impacts of the products, through simplified modules/components.

Designers can identify modules/components which are influent for the use phase (e.g. coil), and modules/components which are not influent for the use phase, but only for the general environmental aspect (e.g. electronic boards).

After this, a preliminary environmental evaluation of each modules can be carried out to understand the environmental consequences of specific choices and quantify the possibility to further improve product environmental performances. Each possible choice is classified by an environmental ranking with a specific environmental score established on the base of literature, previous analysis, generic advices (e.g the most environmental solution for common modules such as “lights”, “electric motors”, etc.)

So, doing, a preliminary idea about environmental impact of different product configurations are provided.

Main Core

<u>Embodiment Design</u>. The third step is characterized by the definition of the overall layout design and the identification of the main features of the products. 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) environmental guidelines to evaluate product concepts results of environmental sustainability analysis;
(ii) results of energy label virtual tests;
(iii) results of environmental sustainability analysis;
(iv) 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. In the embodiment design phase, based on the conceptual design solution selected, the product is defined, and all different design models and respective engineer tools are specified. Different properties and parameters are defined such as the specific material or the specific manufacturing process and designers can study and improve it from different point of views.

In this phase, through the CAD model it is possible to manage a high number of parameters and it possible to make an environmental analysis of the developing product because volumes or geometries, type of materials, manufacture processes are known. This information is necessary to lead a streamlined Life Cycle Assessment, so that the designer can immediately know which components have high environmental impact and immediately modify them. In this way, different scenarios can be studied and there is the possibility to have an environmental assessment of the different choices and give value to the previous guidelines of the conceptual phase. All results of assessments will be collected in the database to create environmental knowledge in the process of solving new problems based on the solutions of similar past problems.

In parallel, from results of virtual tests collected in the database, designers can analyze different product configuration through the parametric virtual model. The virtual model can reproduce the behavior of product studying different configurations and can support the analysis of their energy performances in order to optimize the product in compliance to energy label regulation or energy consumption tests (it depends from the product).

In this way, the designers can study the environmental profile of product using both LCA results and performances analysis of reproduction of virtual tests and they can assess the environmental implication of choices taken during the product design and to improve the product eco-profile by means of alternative solutions at the same time. In this phase, the V.E. database wants to help designers to prevent most of the environmental errors and to manage it since during the virtual design phase. 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.

Capitalization

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.

4.3 Steps of the design process

During the product design process, a designer makes choices, and often he also has to look at the method that will lead to the most ideal product design solution. The goal of the product design is creating a product that fulfils its functions, looks the better possible, can be produced economically and is sustainable from an environmental point of view. This result will be reached by the designer with methods that satisfy the need to change, to solve design process and to respond to new design necessities.

In the V.E Approach an engineering database has been developed to collect qualitative and qualitative information about products which stimulates the knowledge of products and experience with products during design.

Planning and Tasks

In this first step the detailed requirements have to be identified either by demands or wishes. Demands are requirements that must be satisfied in all circumstances (i.e. constraints), instead wishes are requirements that should be taken into consideration whenever possible. To achieve a specific solution, a list of demands and wishes would have to be set up. Requirements must be quantified and defined in the clearest possible terms. The identification of the requirements is a very difficult passage, for the designer is very important understand the customers or the market segment involved. A useful method used to support the preparation of the requirements list is Quality Function Deployment (QFD). QFD helps to translate customer wishes into product technical requirements. It supports a systematic customer orientation of product and process planning. During the last years, the environmental issues are acquiring more importance and so it is important to consider also this aspect in the product design process. In an early stage of the project is not always possible to make precise environmental statements in the requirements list, so they have to be amended and corrected during the design and the development process. To avoid this situation, it is important to support the design in the formulation of requirements more precisely as soon as possible since the early phase of the design process. In this context the consultation of the V.E database take its importance, because the designer, by consulting it, is encouraged in a clearer formulation and identification of new environmental requirements.

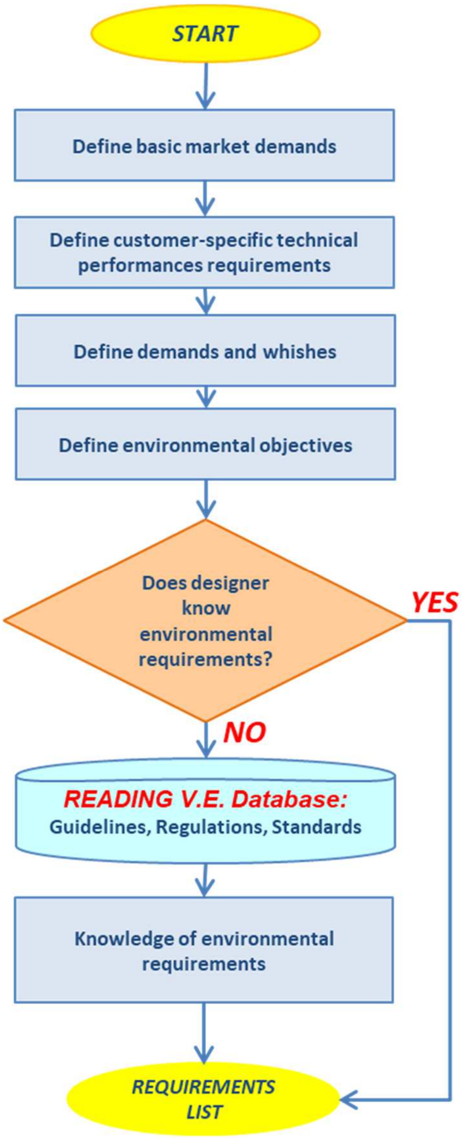


Figure 20 - Steps of Planning and Tasks phase

Conceptual Design

After completing the planning and task phase, the conceptual design phase determines the principles solutions. This is achieved by abstracting the essential problems, establishing the function structures, searching for working principles and then combining those principles into a working structure. Conceptual design can result the specification of a principle solution (concept).

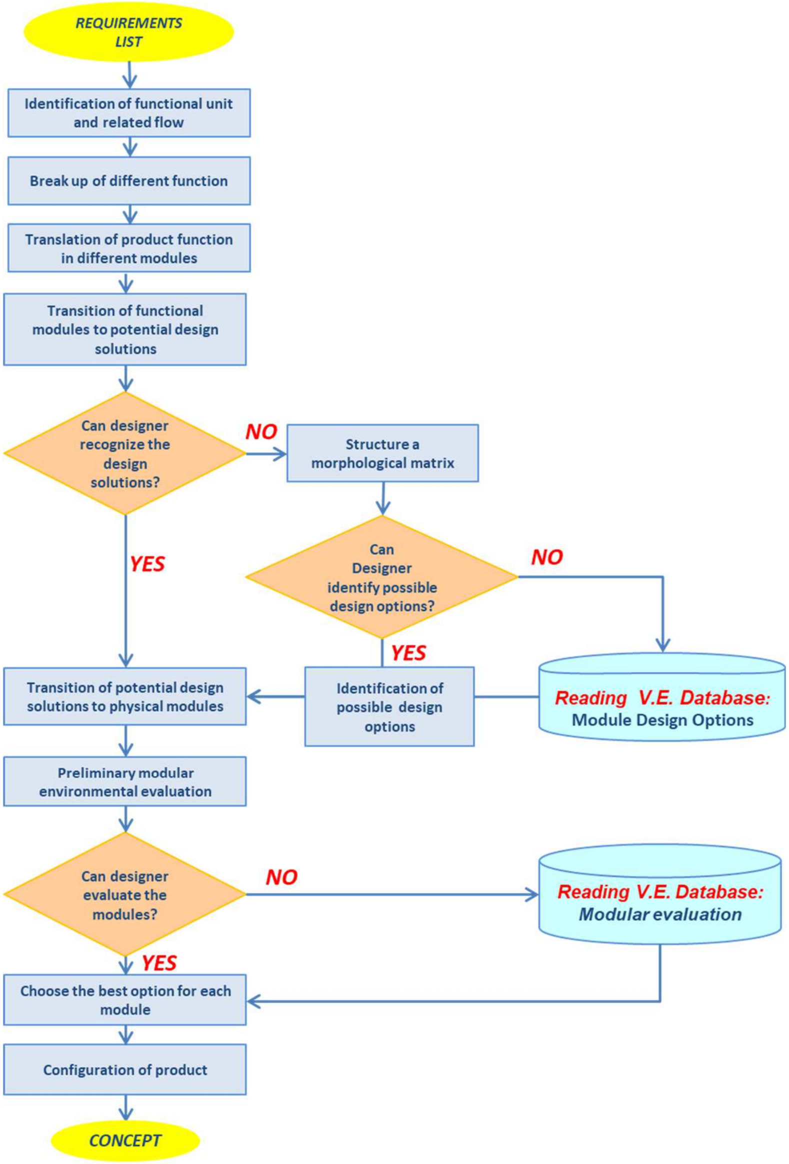


Figure 21 - Steps of "Conceptual Design" phase

Identification of functional unit and related flow: this phase starts defining an overall function of the product that is represented by a black box, and related flows (energy, material and signal).

Break up in different function: This overall function is then split into sub functions of lower complexity. The sub functions are then connected meaningfully to produce a function structure that satisfies the overall function. This step of the conceptual design helps designers and engineers in the definition of the product functions as well as in the identification of the overall product structure.

Translation of product function in different modules: The module heuristics identify the in/out flows of each function. By using this approach, it is possible to translate the product functions into functional modules. Functional modules define a conceptual framework of the product and the initial product configuration. Furthermore, heuristics allows determining the specific properties of each functional module. For each module it necessary to define attributes and properties in order to identify the technical and the functional aspects.

Transition of functional modules to potential design solutions: The transition from product modules to potential design solutions is based on the knowledge of specific properties identified during the generation of the product modules. A very helpful tool at this step is the morphological matrix which can improve the effectiveness of the conceptual analysis.

Structure a morphological matrix: in this step, the morphological matrix is traditionally created by labelling each line with all the identified product modules and, for each module, the possible design options, listing the solutions as columns and the product module as rows. In the V.E database are stored simplified model of each possible design options of the product, in order to support the designer in the choice.

Transition of potential design solutions to physical models: The morphological matrix finally shows existing alternative design options for each functional module of complex system and it permit a rapid configuration of the product with the selection of the best option for each specific module.

Preliminary modular environmental evaluation: in this step a description of the future product is abstract and information regarding final attributes of the product that determine its future environmental performance and lifecycle is available only from the concept evaluation where alternative modules are compared according to a set of evaluation criteria and requirements. In this step the role of the V.E. database acquire its importance, because through specific scored guidelines, designer can classify each module and evaluate the most environmental feasible. The collection of guidelines and their classification is stored in a specific section of the database.

Choose the best options for each module: In this step, after the environmental evaluation the designer have the possibility to choose among different alternatives taking into account environmental friendliness criteria and it is possible an eco-evaluation since the product concepts.

Configuration of product: In this step, the large number of variants has to be reduced to one concept to be pursued. The aim of this step is to focus on the working principles, components or parts of the structure that are essential for the evaluation of the concepts and the selection of the one that will be transferred to the embodiment stage.

Embodiment Design

During this phase, designers, starting from a concept (working structure, principle solution), determine the construction structure of a technical system. The result of the embodiment design is a layout.

Embodiment design is a part of the whole design process in which, the product concepts gets concrete form in accordance with technical and economic criteria. The principle solution has been elaborated during the conceptual phase and in this phase the underlying ideas can firmed up. During the embodiment phase, designers must to determine the overall layout design, the preliminary form designs and the production processes.

In fact, it is often necessary to produce several preliminary layouts to scale the advantages and disadvantages of the different variants. The evaluation of the different variant may lead to the selection of one that looks particularly promising, even with a preventive appropriate combination and elimination of the weak spots, supported by V.E. database. Embodiment design involves many different steps in which the research of solutions and evaluation are present. In the elaboration of the embodiment design, many details must be clarified, confirmed and optimized. In these different steps the V.E. approach takes place, even it is a complex process in that many actions must be performed simultaneously, and the process will proceed from qualitative to quantitative, from the abstract to concrete.

Identification of embodiment requirements: the first step is to identify the requirements that have a crucial importance in the embodiment design, material requirements, direction of flows, positions, installation requirements, etc.

Identification of the main embodiment functions: In this step, taking into account the concept, a rough design is produced with the attention to the assemblies and the components fulfilling the functions recognized in the conceptual phase. This identification allows to determine the size, the arrangement and component shapes of overall layout, similarly to the division in modules of the previous conceptual phase.

Development of a preliminary layout for the embodiment functions: preliminary layouts must be developed in this step. The general arrangement, component shapes and materials must be determined provisionally. In this phase, the designer can consult the V.E. database in order to find a valid support for a possible design solution. In database in a specific section simplified CAD model are stored and file containing material guidelines.

Preliminary product layout: The result of this step is a preliminary CAD product design, in which the overall spatial constraints meets the relevant main function fulfilled. Known solutions and existing components are presented in simplified forms presenting one or more suitable preliminary layouts and providing also new knowledge to collect into the database in order to upgrade it and making available this experience for further future design.

Development of product layout ensuring performances and optimized configurations: In this step, the preliminary layout of previous step have to be developed for the remaining main functions which that have not yet been considered because known solutions exist for them or they are directly linked with the performances required to the product. A detailed layout must now to be developed in accordance with the embodiment design phase, paying attention to standards, regulations, detailed calculations and also the compatibility with the different function that have been realized. In this step the product layout requires several concepts to be put in more concrete form, above all from a performances point of view. In fact, in this phase the support of the V.E. Database is fundamental, in particular with the consultation of the V.P Previous studies, which contains virtual tests, performances, configurations parameters, a design can study the product preliminarily. The V.P. studies collect data from testing and simulation, in fact the behaviour of model is presented in the database as a collection of data, tables and curves reproducing the operational phase of the product, in compliance with the directive. In particular, data which comes from simulations focused on FEM and CFD solvers in order to analyse the behaviour of the product in terms of performances, energy efficiency and consumptions. By consulting V.E. Database, this step addresses the designer to study a possible optimization approach of the product. The designer can configure the product using optimization analysis.

In the database are stored data about the optimization of the product using a DOE approach, based on CFD and FEM analysis to study the performances, taking into account possible critical point that, in other situations, can be identify only in following steps. While different possible product configurations have been analysed by simulations, others can be tested and collected in the database in order to increase the knowledge.

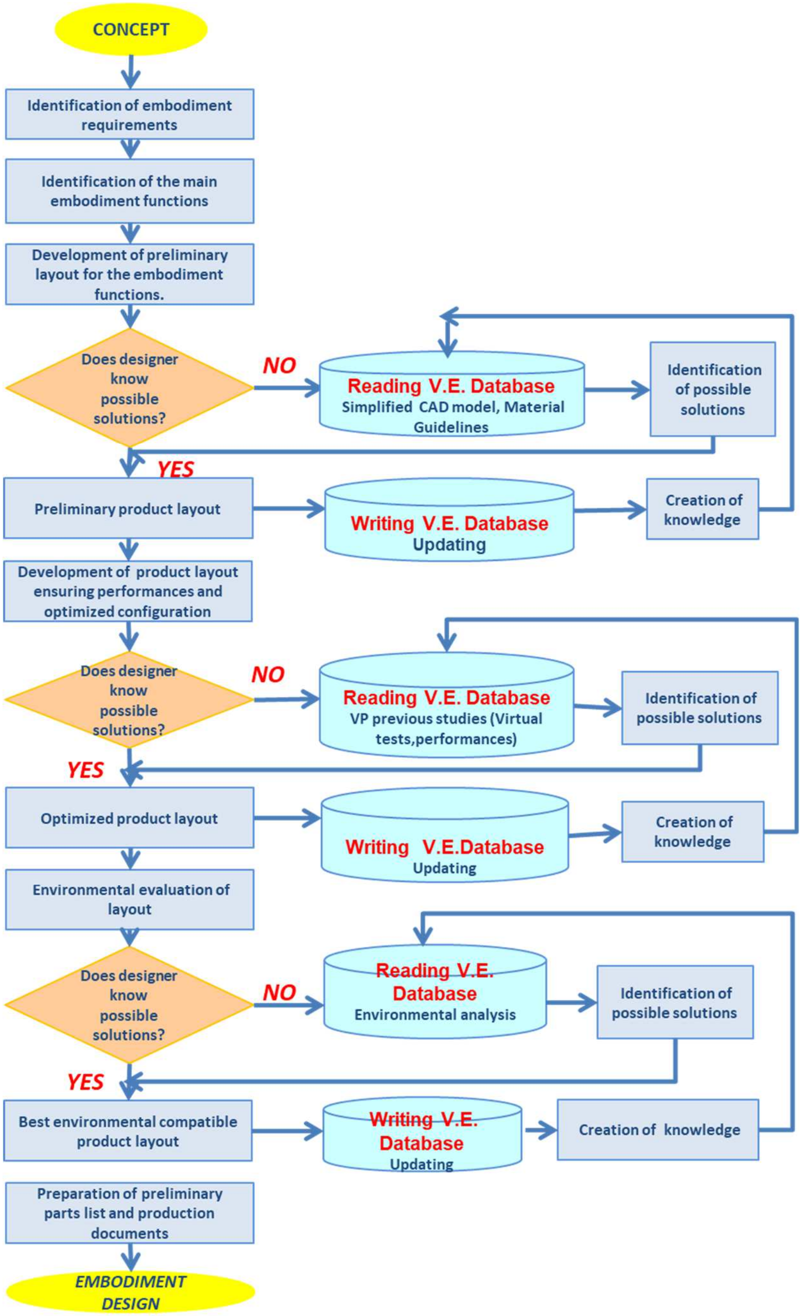


Figure 22 - Steps of "Embodiment Design" phase

This aspect proves advantages, because avoid repeating the previous steps and allows to adopt suitable solutions. Using the V. E. approach, it is thus possible, to take important decisions since this step, while in other cases the decisions will have to be deferred until after a more detailed design.

Optimized product design: In this step the preliminary overall product design is fixed and describes the complete construction structure.

Environmental evaluation of design: In this step, it possible to have an ecological assessment of the product. The sustainable product design is one of the aim of the methodology with consideration for environmental impacts of products during the design process. During the embodiment it is possible determine the environmental assessment of the product. In this step the embodiment product design evaluation is a progress to evaluate product sustainability since the design stage. Using this preliminary environmental assessment, it possible to quantify the environmental impact of the product and evaluate if the design choices made are possible. Each new different evaluation will be stored in the database in order to create eco-knowledge available for further design project.

Best environmental compatible product design: After the environmental assessment, made by new LCA analysis or consultation of eco-knowledge stored in the database, the design can have the best environmental compatible product design, considering the boundary conditions of the design.

Preparation of preliminary parts list and production documents: Conclude the embodiment design phase by preparing a preliminary parts list as well as a definitive layout ready for the detailed design phase.

Detailed Design

This is the phase of the design process in which the arrangement, forms, dimensions and surface properties of all the individual parts are finally laid down, the material specified, production possibilities assessed, and all the drawings and other production documents produced.

Product

In this step the product configuration is available and if it is frozen can be stored in the V.E. database. At this time, the requirements of the product are satisfied, and each choice made during the process became knowledge to collect for further improvements. Clearly, at this step, the product is real and experimental performances tests and environmental assessment can be carried out, if a product review is required. In addition to the tests, in this phase could be important to grow the database also with user’s feedbacks during usage and end of life treatments in order to have a more complete overview of product.

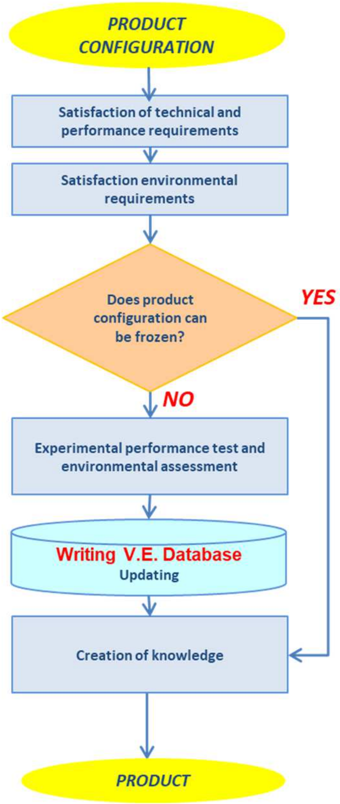


Figure 23 - Steps of "Product" phase

Chapter 5.

The database: Virtual Eco-design Database

5.1 The structure of the database

The increasing global competition and dynamic market lead companies to focus on product design and its correlated technical problems. Designers often turn to technical database to seek inspiration and this need makes the process of knowledge management an urgent question to survive in a world dominated by innovation. In order to overcome the limit presented in literature, the V.E. approach have been developed to foster eco-design in industrial companies.

The core of the approach is represented by its database, in which in specific sections eco-design guidelines, virtual prototyping studies and lifecycle analysis are stored and organized in order to facilitate their consultation. V.E. database allows to collect all information about product design and redesign.

V.E. database is characterized by a constant upgrading with ongoing accumulation and revision to stay current. Since the product design knowledge has its own lifecycle, designers need to capture new knowledge and utilize it to improve product quality.

The choice to implement a database in the V.E. approach is based on the knowledge process construction, which is divided into three stages: creation of knowledge, use of knowledge and maintenance of knowledge. The adoption of a data storage technology as a key method to address these issues is the solution to allow that the information returns in a structured way, consistent with the human knowledge processes, in opposition to a simple disorganized list of items. The database retrieval organizes the information indicating indexation, connections between different elements and knowledge sharing. The sharing of knowledge and the relationship between the database and the user can be summarized by two main actions, “reading” and “writing”, as presented in the previous sections (Figure 20, Figure 21, Figure 22, Figure 23). The user “reads” the database when need a support during the design process and “writes” the database to create knowledge. At the same time the database has also a more active role, because it shows the potential of the variation of information through the design process. The database can not only be used to supply eco-design knowledge in terms of product concepts and attributes, but also to supply a guidance on what procedures to follow.

The database does not classify every perspective of design knowledge but bring meaningful and relevant information to designers using a structured organization of information.

The database is structured in different levels as presented in Figure 24:

(i) As a repository of environmental guidelines and design tool to support decision-making process oriented to eco-design.

(ii) As a repository of virtual analysis in different product configurations (materials, dimensions, etc.)

(iii) As a repository of environmental analysis

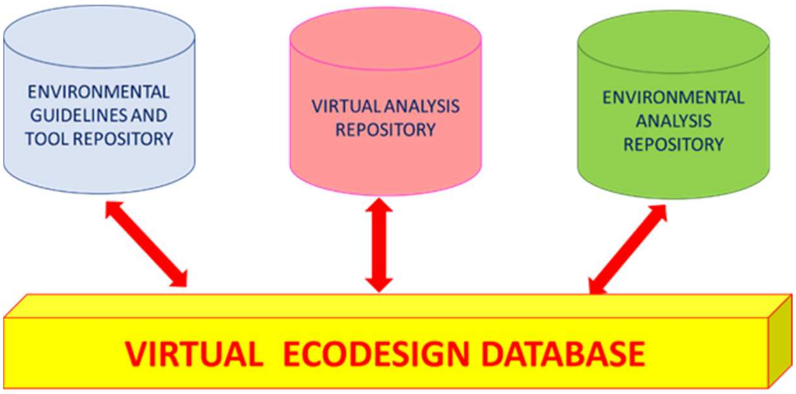


Figure 24 - Structure of V.E. database

At its first implementation the database includes only eco-design guidelines retrieved from literature, virtual simulation derived by preliminary analysis, past environmental studies. Later, during the use, the company will update the repository with acquired knowledge. The database is filled every time a new virtual simulation is performed, or every time a new guideline is derived from company or every time there are LCA results of new product. This information can be stored in the database sections and reused by designers for the environmental evaluation of product modules/components during the design phases.

In this study one of the most important objective is to create an automatic database that manage knowledge properly so that users just have to use it in a simple and quick way. During the design process, designer can consult the three sections of the database following a hierarchical order mirrored in each phase of the product development. Excluding the first section, which is represented by a little repository and related tool, the second and the third section can be consulted by queries formulated using key-words which are linked to the documents.

The developed database allows the management of knowledge as a systematic process of creating, maintaining and encouraging a company to use knowledge in order to get competitive advantages or get high performances in the sustainable matters. The creation of database is an approach to the management of companies, in which knowledge has a fundamental and central role, bringing tools of different functions and allowing creation and sharing of knowledge.

The product process design is a combination of knowledge and experience from different sources as technical documents, designer skills, company requirements. The development of the V.E. database is studied and evaluated in order to support designers in discovering and managing eco-design and design knowledge. With such database, the information can be organized with a comprehensive and universally accessible way, which provides a path for innovation, or exploration and integration.

V.E. approach and its database permits to create a company knowledge that can be shared among the designers and engineers inside a manufacturing company. In particular, knowledge is created 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.

Designers may also find designs closely related to the previous design and utilize the available information. A successful design depends on the relative design knowledge and field experience. In order to use this knowledge, the database is built through a process of data collection, mining, integration, management and maintenance.

In the following sections, there is the detailed description of each database level.

5.2 Environmental guidelines repository and tool

5.2.1 Environmental guidelines repository

In order to fill in the V.E. Database with eco-design guidelines, the analysis of literature related to this topic have been realized.

Literature defines guidelines as “procedures to orient a decision process towards given objectives” (Bonvoisin, 2010) and their major functionalities are giving a wide list of promising strategies before any implementation choice and allowing the assessment of the focus towards an objective. In this case, the guidelines have to be applied on the design activities of the product development since the conceptualization, pursuing the objective of the minimization of the environmental impact.

A literary analysis showed that a high number of eco-design guidelines exists, and they often provide only general indications to designers. This generality makes, from one side, eco-design guidelines referable to a lot of different design process stages, but on the other one, it does not guarantee their efficacious consultation by designers, and their effective translation into design choices (Vezzoli et al., 2006); (Luttropp et Lagerstedt, 2006); (Koh et al. 2007).

As identified by Hallstedt et al (Hallstedt and Thompson, 2011; and Hallstedt et al., 2013a), in order to guarantee their effectiveness, environmental guidelines must have specific features:

- Have to be compliant with the company sustainability requirements;
- Incorporate a back-casting perspective from a definition of success;
- Include decision aspects concerning product life-cycle phases (from raw material to end-of-life phase);
- Include sustainability aspects that cover a sociological sustainability perspective, guided by sustainability perspective.

The process of identifying guidelines is composed by different steps, as recognized by Hallstedt (Hallstedt et al., 2013):

- ***Collect existing sustainability and tactical design guidelines***: this step is based on the identification specific sustainability guidelines that are relevant today. The purpose is to identify and collect guidelines which can come from different sources, such as product requirements, company requirements, industry requirements. Many of these requirements can be formulated as qualitative targets or can be in double and triple versions, only with a different formulation.
- ***Review all product life-cycle phases through sustainability principles*****:** In this step guidelines are organized by mapping out in detail the main phases of a product life cycle and considering decisions aspects for these lifecycle activities.
- ***Reduce and select guidelines using specific criteria***: the goal of this step is to derive a manageable and applicable list of design guidelines. The set of design guidelines will then represent the prioritized sustainability aspects to be considered during product development. In this way, the sustainability design aspects to be considered during the development and the evaluation of products and concepts are defined. Hallstedt defined a set of criteria, established and adapted from Shmidt and Butt (Shmidt and Butt, 2006) and Dreyer (Dreyer, 2010):
    - *Applicability:* guideline must be applicable to different concepts.
    - *Logic and Simplicity*: guideline needs to include a design objective that has an unambiguous measurement rule and measurement unit.
    - *Feasibility/data availability*: guideline must draw on information that is possible to obtain;
    - *Clarity:* Each design guideline has to include a design objective that has a measurement entity;
    - *Relevance:* guideline must represent aspects of the sustainability dimensions.

These criteria have equal importance and the guidelines have to be formulated in order to prioritize design objectives. The main purpose of environmental guidelines is to support product developers and design teams in the development, evaluation and selection of concepts during the early product development phases. The main role of guidelines is to give guidance in the pre-design phase when developing and selecting new concepts ideas and to support decisions during development of them.

The most important objectives of guidelines in this eco-design approach is to give support for a qualitative assessment of a concept or a comparison of different concepts from a sustainability perspective.

5.2.2 A methodological and adaptable tool

The V.E. methodology and consequently the guidelines tool are based on the concept that designers need assistance when they design and re-design products with the objectives to improve their environmental performances. In fact, designers and companies do not have the necessary knowledge on environmental sustainability and the necessary time to conduct specific analysis, for this reason, the guidelines tool has the objective to satisfy this gap and to be useful for designers and usable within different companies.

Guidelines can therefore be considered as generic, in fact the tools have been conceived in order to allow companies to reach a desired level of specificity and linkage with the company constraints. The tool is completely customizable, and company can update criteria and sub-categories, in fact companies can add criteria linked to their specific requirements or can insert new guidelines which are more practical and adapted to their specific products or modify existing ones for the need of the company.

Besides the elaboration and the organization of specific guidelines, it is very important to define a process aiming their real integration into company realities.

It is important to highlight two main properties of the tool: the **usability** and the **applicability,** which are referred to the integration in the company's existing procedures and to the design teams which use it. These are two crucial aspects of the methodology and of the tool implementation. In fact, the usability underlines the degree to which the tool can be used by designers to achieve quantified objectives with effectiveness, efficiency and satisfaction in the specific context of eco-design. The applicability highlights the possibility to makes factual since the early design phase the sustainable suggestions derived from guidelines.

In fact, it is clear that if accompany without eco-knowledge decides to adopt the proposed tool, the guideline database will include only eco-design guidelines retrieved from literature, latter during the use of the tool, when company will have acquired knowledge and skills, the eco-knowledge will be different and specific for each company.

The guidelines tool workflow (Figure 25) can be summarized in the following steps:

1. *Definition of the product concept*: during the conceptual phase of the design process, the designers and the engineers defines the aim of the project and the target parameters to reach. In fact, the definition of the concept needs a support to check if they have considered certain environmental aspects. The tool helps users to define measures that can be used to address the sustainability issues.
2. *Consultation of guidelines database*: In this step, the involvements of designer begins. They know what the company objectives and the consultation of guidelines database are in the V.E. database can help them to acquire the necessary know-how on the environmental aspects during design process. In particular, they need to consult some general eco-design guidelines related to the product they analyse, in order to identify possible strategies to reduce the environmental impact.
3. *Filtering of guidelines*: In this step guidelines are filtered through attributes in order to highlight particular aspect focusing on sustainability. In fact, the

main environmental criticalities of the product are identified and through a smart filter they can acquire knowledge on eco-design issues.

4. *Guidelines with eco-design score and application of guidelines*: In these steps, the process of finding solution to realize a product that is in compliance with the sustainability principles is initiated. Users acquire awareness on environmental matter under the guidance of guidelines evaluated with the eco-design score. The eco-design score introduces them to the sustainable development of concepts and enable users to initiate and monitor environmental aspects during the design process in a structured way in situation that are characterized by a lack of information and high degree of uncertainty.
5. *Evaluation of applicability of guidelines and customization of guidelines database:* In this step, the solution for the problems detected are developed further. Solutions to customize the tool and to prioritize specific action to contribute the getting of sustainability goals. In each guideline the user can store notes and can add some considerations about its applicability or its usefulness in the company point of view. This step is a dynamic process that involves appropriate solutions to make flexible the tool based on company tasks and environmental goals. The aim of these steps is to improve successfully the feasibility during conceptual and also simultaneously during others engineering phases.

The defined guidelines can illuminate previously unexplored design sustainable design aspects or constrain the design aspects to reduce environmental impacts. The designer can use guidelines to map the design dimensions and to understand limitations and opportunities before identifying plausible concepts. There are some characteristics, including both strengths and weakness, of the suggested approach in defining the sustainability guidelines which could give guidance for a company. Sometimes, many advanced and complex solutions need to be analysed in the environmental question. In fact, some actions can represent a significant risk for the company because could affect investments plans, quality control and efficiency. In the application of tool for a company it is important to evaluate all the aspects of the environmental solutions suggested by guidelines, including aspects of today together with aspects of the suggested solutions from a future sustainable perspective. These aspects represent important features for the customization and the analysis of the applicability of the tool. Users need an instrument to evaluate the applicability and to make more effective the customization of tool, in fact the introduced applicability score, which explained in the next section, can be used to give guidance on the current level of environmental aspects in the design process for a company and how to improve the sustainability profile.

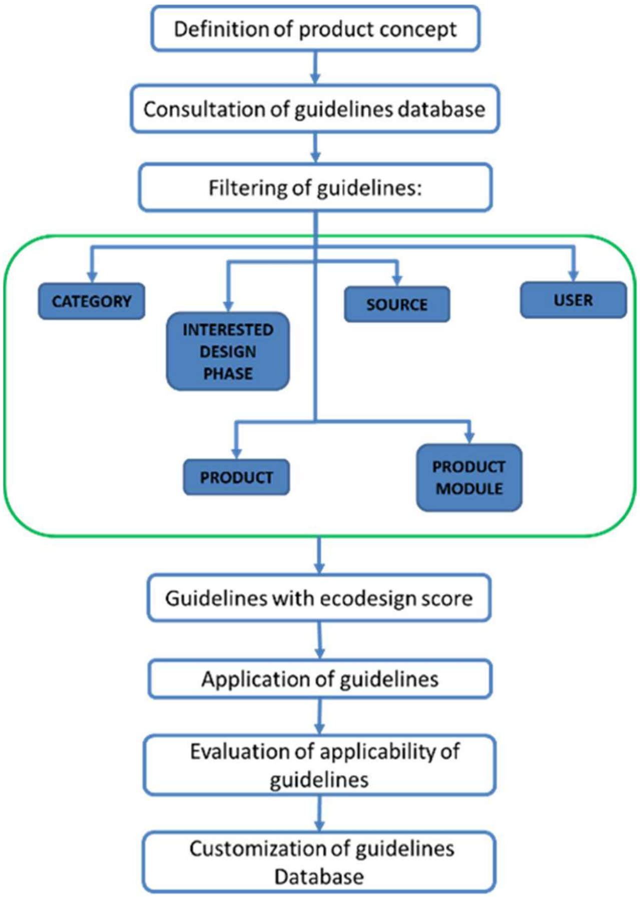


Figure 25 - Guidelines tool workflow

5.2.3 Guidelines: list and classification

The guidelines (presented in the Appendix A) have been analysed and stored in the database by eco-design researchers to have critical point of view and to have a quantitative evaluation of its relevance in terms of environmental sustainability. They have been collected from standard, regulation related publications, conference proceeding and journals (Bonvoisin et al, 2010)(Wimmer et al, 2005) (Luttropp and Lagerstedt, 2006), (Wever et al, 2008)(Rose et al,1999), (Eco-design Pilot, 2015) (Vezzoli and Sciama, 2006), (Dahlstrom, 1999) (Bischof and Blessing, 2008), (Koh et al, 2007) and their formulation has requested a great study in terms of time and comprehension from literature. This meant that the collected data and information about existing sustainability requirements and guidelines were crosschecked by using multiple sources. More specifically, the guidelines were collected from a variety of sources, such as product requirements, company requirements and goals, existing regulations and tools. The preliminary findings have been validated with pilot tests, and iteratively discussed with stakeholder group, engineers' groups active in the early phases of product development process. Reflective learning for the researcher has been aided by the continuous participation of the stakeholder group in regular debriefing activities. This work builds on ideas from an introductory approach for sustainability integration since the early phase of product design, with the focus on establishing requirements and drivers for design including a sustainability perspective.

The guidelines should inspire and indicate the decision/solutions that have the major potential to be environmentally sustainable and they should provide the specific advice and strategies (Dahlstrom, 1999). Eco-design guidelines are a simple tool used to help designer achieve a more environmentally compatible design. Generic guidelines are presented (Luttropp and Lagerstedt,2006) (Brezet and al., 1997) (Meinders, 1997) (Koh et al, 2007) (Telenko et al.,2008) (Namikawa, 2005) in literature and their application can be very transposable for managing eco-design objectives and in the product development process, but their possibility to evaluate the product was too general and not able to provide information and a comprehensive overview of how to rank the product concepts. It is necessary to have guidelines more incisive in the description of environmental dimension.

Guidelines are defined with attributes and collected with hierarchical organization, and each one is ranked by an **eco-design score**. The goal of the tool is to derive a manageable and applicable list of design guidelines which are kept as short and as simple as possible.

The aim of the hierarchical organisation is to structure the guidelines in order to allow the user efficient filter and consequently choice of them according to the design context. The organization of guideline aims to the quality of decision-making process, supporting the specificity of guideline in the product typology, in the design phase, in the environmental category and user. In particular, aims to support what have to be decided, where have to be applied, when have to be considered and who is the user.

The guidelines are organised in the form of table and classified on the base of following attributes:

- ***Product Type*:** guidelines can affect different products. Some are involved in different types of product, so it is necessary to specify it.
- ***Product Module***: guidelines can affect different physical hierarchy of the product. Some are involved in to definition of the entire "product", or the specific "module", dealing with the modification of product/component functions.
- ***Interested design phase***: the usage of guideline is linked to the stage in the design process. This attribute specifies the stage when the decision to implement a guideline can be made. The choice list is based on the standard Pahl and Beitz design process (Pahl and Beitz, 1996) ("planning and tasks clarification, conceptual design, embodiment design, detailed design).
- ***User*:** Some guidelines doesn't concern every type of users but propose a specific solution for a particular technical figure which have to be involved

in the implementation of guideline. In this case the choice has been made on the base of the general figures present in technical departments of company supplier of mechatronic products (mechanical engineer and electrical engineer).

- ***Source:*** this category specifies the source of guidelines. A guideline can be found in literature, but also can be collected from experience of designer, eco-design researcher or company knowledge.
- ***Category:*** the category ensure that a comprehensive analysis of sustainability issues can be made. Starting from a literary analysis, the specific sustainability issues that are relevant are identified in these categories: design, material, energy consumption, toxicity, safety system, recyclability. They ensure that a comprehensive analysis of environmental issues can be made. Byggeth et al.,2007)(Byggeth et al.,2006) (Wimmer et al., 2004)(Brezet and Van Hemel., 1997).
    - Design: the category considers the large general aspect to be considered in the design phases, concerning overall product or its module, reduction of weight, optimization technique etc.
    - Material: this category covers all aspect that are related to material usage, selection of low impact materials, renewable materials, materials with positive social impact.
    - Energy consumption consider the reduction of impact during use, reduction of wastage of energy and other consumables:
    - Toxicity concerns the toxicity of materials, of production process.
    - Safety system consider the health and safety aspects of the product both ethical and general.
    - Recyclability includes the aspects concerning the reuse, recoverability and recyclability potential of the product.

Thanks to the association of these attributes to each guideline, the user can filter and easily retrieve them according to his/her objectives.

The aim of the prosed tool is that guidelines collected in the database can be considered as potential tool for designers for establishing design strategies from ecological point of view and can be used for evaluation purpose. The proposal addresses the problem of performing an Eco evaluation of product concepts in the early decisive design phase of the product development using guidelines ranked with specific eco-design score.

5.2.4 The Eco-design Score

Eco-design Score of guidelines give a support for a quantitative and qualitative assessment of a concept or a comparison of different concepts from a sustainability perspective, during the early design phase of product development.

The evaluation is an important aspect to derive an applicable and manageable tool, because besides the elaboration of specific guidelines, it is important to establish a guideline priority. This should be defined on the basis of its potential environmental improvement.

In this perspective it is important to establish guideline priorities from an environmental point of view, in fact they should be defined on the basis of their environmental impact on the product, according to their potential environmental improvements.

Eco-design Score is an aggregated score calculated on the sum of the contribution of the subcategories of three criteria. The three criteria represent the aspects to be considered during product development and the aggregated score, computed according on the relevance of guidelines on subcategories, gives the final result.

The highest value of relevance is 10, and consequently lower values indicate lower relevance.

The aggregated score shows how the importance of the environmental aspect can affect product development and the sustainability dimension links the internal design process, the four life cycle phases and the different dimension of sustainability.

The three criteria with relative subcategories are following:

- SUSTAINABILITY DIMENSION (Ecological, Social, Economic);
- LYFE CYCLE PHASE (Engineering, Production, Use End of Life);
- PROCESS DESIGN PHASE (Conceptual, Embodiment, Detailed);

SUSTAINABILITY DIMENSION

Sustainability dimension has three main pillars: economic, environmental, and social.

Ecological: Guidelines influence the ecological aspect of product development which means that the natural resources, such as materials, energy fuels, land, water are consumed in a sustainable rate.

Economic: Guidelines influence the economic aspect of product development which means that resources are used efficiently and responsibly to produce an operational profit.

Social: guidelines influence the social aspect of product which means that the social wellbeing of a country, an organisation, or a community can be maintained in the long term.

LIFE CYCLE PHASES

Each phase of lifecycle contains specific categories which can be environmentally improved by guidelines, listed for each one as follows:

Engineering: use of low impact materials, optimization of material input, use of renewable materials, weight reduction, use of recycled materials, health and safety aspects, modular product.

Production: social and ethical issues in the supply chain, resource efficiency in production, resource consumption in production, transport efficiency, safety, toxicity process, transport and logistics.

Use: Energy consumption reduction, decrease of the environmental pollution, resource consumption, economic efficiency and profitability.

<u>End of Life:</u> reuse, recycling, Disposal, Recyclability.

PROCESS DESIGN PHASE

Guidelines can be applied since specific phase of process design and can drive designers to environmental dimension:

<u>Conceptual</u>: Designer conceives general solutions to reach the tasks defined in the first step following environmental guidelines. Definition of product modules and architecture with "high level" features.

<u>Embodiment:</u> Designer defines product layout and features (using CAD tool). Designers can consult Consulting guidelines, designers are supported in the definition of new possible product improvement strategies

<u>Detailed:</u> Designer defines technical drawing of assembly and components and performs experimental tests, and the relevance of guideline can be verified also in this phase.

The three criteria were defined together with subcategories starting from a literary research process to encourage users to think about the environmental aspects in a global perspective of product development (Robert et al, 2002) (Robert et al., 2013). To cover a complete idea of sustainability, the criteria have been built in order to allow to consider the potentiality of guideline on a full life cycle perspective, on the applicability in the product development phases and the consideration of a specific sustainability dimension or all three dimensions (Pierini and Schiavone, 2006),(Johansson, 2006), (Kengpol et al, 2011) (Baumann et al,2002), (Bhamra et al,1999).

The table shows the evaluation scale of the score:

8 - 10	**Very Relevant**	Guideline influences all or almost all the product development aspects presented in the three criteria. Its application is necessary and can introduce a real sustainability dimension in the product development since early design phase. A very relevant sustainability perspective is considered.
7 - 5	**Relevant**	Guideline influences some important development aspects presented in the three criteria. Its application is important can introduce a sustainability dimension in the product development since design phase. A relevant sustainability perspective is considered
3 - 4	**Classic**	Guideline influences basilar aspects of product development and introduce general sustainability dimension in the product development during design phase. A classic sustainability perspective is considered.
0 - 2	**Not relevant**	Guideline influences few or no aspects of product development and doesn't introduce a sustainability dimension in the product development. A not relevant sustainability perspective is considered.

Table 3 - Evaluation scale of Ecodesign Score

5.2.5 Applicability Score

Applicability score is the instrument for product developers or design teams working in the early phase of product innovation process and/or environmental engineers to investigate the applicability of guidelines for each product module.

The assessment of the applicability of environmental guideline have to be test in different settings at the case company to have an indication and evaluation of the ability of guideline to give guidance and support in bringing in a sustainability perspective when developing, evaluating, and selecting different concepts in the early phase of product development. These score gives indications of the relevance of the eco-design score and ideas for improvement in sustainable point of view for a company. The purpose of the applicability score is to get some ideas for integration possibilities in the company's decision support system.

The assessment of guideline from a company's point of view is important in order to define what sustainability means for company in decision support during the design process, and also how the sustainability can be achieved using specific guidelines. The score can be considered as a guidance to identify how sustainability application can be measured for a company and how it can make its processes and its products more sustainable.

The applicability score gives the possibility to the company to evaluate its role in the pre-design phase when developing and selecting new concepts and whether the guideline can be followed and applied, providing a scoring system of evaluation. During the assessment, the designers and engineers who evaluate the applicability of the environmental guideline must state the its relevance in the design process and whether they can consider it. In fact, the guideline can be applicable from a general point of view, but not applicable because of other tasks depending on company target. These targets can be various, such as economic, operative, internal policies…et al.

This evaluation can represent an important potential for improvement and creation of strategic environmental priority.

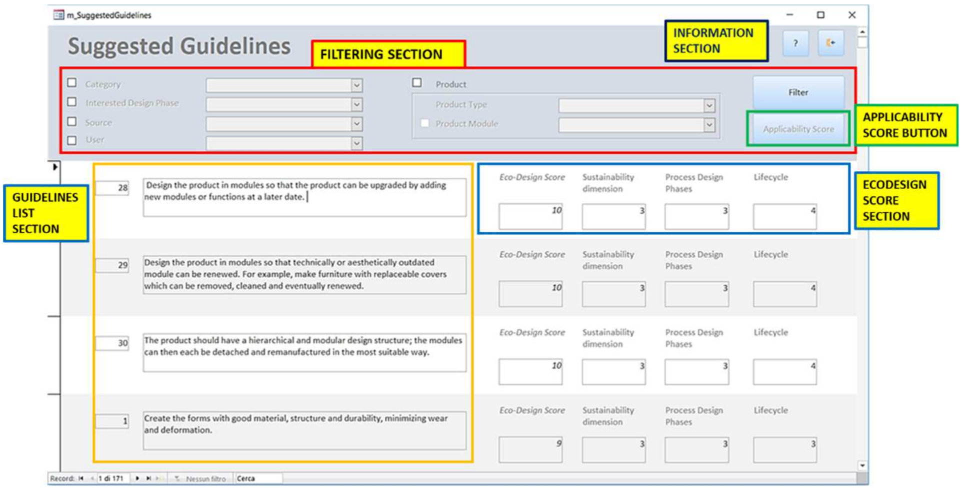
The evaluation grid is defined as follow:

8 - 10	The sustainability criterion is fulfilled.
7 - 5	Have implemented a strategy with concrete actions for how to move stepwise towards more sustainable solution. Moving strategically towards the excellent level.
3 - 4	Compliance with ecological related regulations. A low but acceptable level.
1 - 2	Lowest level of sustainability applicability.
0	No information. Need more research and investigation.

Table 4 - Evaluation scale of Applicability Score

5.2.6 The structure of the guidelines tool

The core of tool is represented by a database of more than 100 guidelines gathered from literature and ranked from an environmental point of view using an aggregated eco-design score. The main users of the tool are designers, which use it when they want to re-design or design a product with the objective to improve their environmental performances. Users can consult the eco-design guidelines and acquire knowledge on sustainability matters. At first implementation of database, users consult guidelines already environmentally ranked by eco-design experts. The eco-design score is present in the tool since the initialization of the system, instead the user has to classify the environmental guidelines using the applicability score.
In parallel, they can store into the database new guidelines they consider useful for design and classify them both with the eco-design score and both with the applicability one which describe their applicability in the company contest.
The tool has been developed in order to be very easy to be used also by non-expert designers, and its interface reflects this objective (Figure 26).



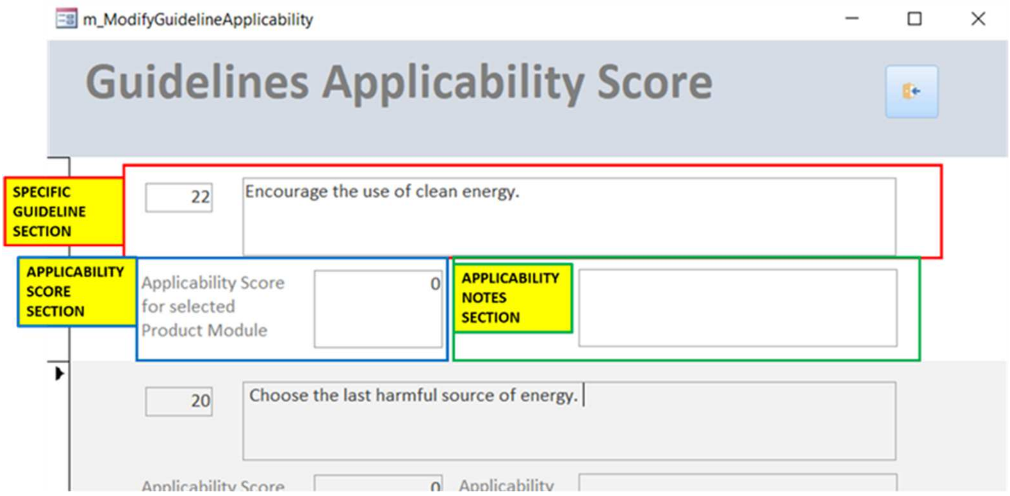
		Eco-Design Score	Sustainability dimension	Process Design Phases	Lifecycle
28	Design the product in modules so that the product can be upgraded by adding new modules or functions at a later date.	10	3	3	4
29	Design the product in modules so that technically or aesthetically outdated module can be renewed. For example, make furniture with replaceable covers which can be removed, cleaned and eventually renewed.	10	3	3	4
30	The product should have a hierarchical and modular design structure; the modules can then each be detached and remanufactured in the most suitable way.	10	3	3	4
1	Create the forms with good material, structure and durability, minimizing wear and deformation.	9	3	3	3

Figure 26 - Interface of guidelines tool

The main sections which compose the tool interface are following:

- **Filtering section** composed by several combo boxes which allow the user to query the database according to specific attributes.
- **Guidelines list section** in which guidelines and company knowledge retrieves from the tool according to the filtering options, are shown to the user.
- **Eco-design score section** where the values of the three criteria which compose the aggregate value of the final score are shown.
- **Applicability score button** which allows to open the applicability score section where the user can evaluate the applicability in the own contest of the guideline. This button lights up when the product module is selected through the filtering operation.
- **Information section** which summarize the criteria and the evaluation grids of the "applicability score" and of the "eco-design score".

The main interface of the applicability score section is presented in Figure 27:



m_ModifyGuidelineApplicability

Guidelines Applicability Score

22 Encourage the use of clean energy.

Applicability Score for selected Product Module: 0

20 Choose the last harmful source of energy.

Applicability Score: 0

Figure 27 - Interface of Applicability Score section

It is composed by three main sections:

- **Specific guidelines section** where the specific guidelines for the product module selected in the filtering operation is shown;
- **Applicability score section** is the specific section for the customization of the tool by company. In this section the user can enter his evaluation about the applicability of guideline for the selected product module in relation to the company mission, context or pragmaticistic suggestion in the design process.
- **Applicability notes section** in which the user can write comments or suggestion about the specific guideline and its application.

5.3 Virtual analysis repository

Literary reviews show the increasing relevance of Virtual prototyping in product development, with the employment of modelling and numerical simulation techniques.

Rapid use and refinement of computational methods are leading to incredibly fast growth of VP technology, increasing its robustness, accuracy and precision (Chang et al. 1994). Currently, a great number of software is involved in VP: 3D CAD systems, finite element analysis (FEA) and computational fluid-dynamic (CFD) tools (Hughes et al., 2000) (Cook et al., 2001) (Liu et al., 1998).

The virtual prototyping is a numerical simulation of a virtual product model that can be analysed and tested from different aspects (design, engineering, performances, manufacturing, configurations parameters, behaviour, 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.

Virtual analysis can extend the range of information about the product, in fact the models can be applied to simulate how a specific combination that has been tested following selected conditions would perform under different ones, thus allowing for protocols and tests comparability without the need to actually perform multiple and different experimental campaigns.

This section of database is based on the storage of virtual analysis and their comparison with experimental results in order to guide the generating process of product design.

The virtual analysis repository (Figure 28) tries to improve product design by exploiting different product configuration and efficiency performances (accumulated by experiments and CFD, FEM calculations results). The availability of database can help to increase design efficiency since the early phase of product development.

This can help to understanding -already in the design phase- if a given product is capable of meeting the environmental and market requirements, and how the performance varies as a function of these two aspects.

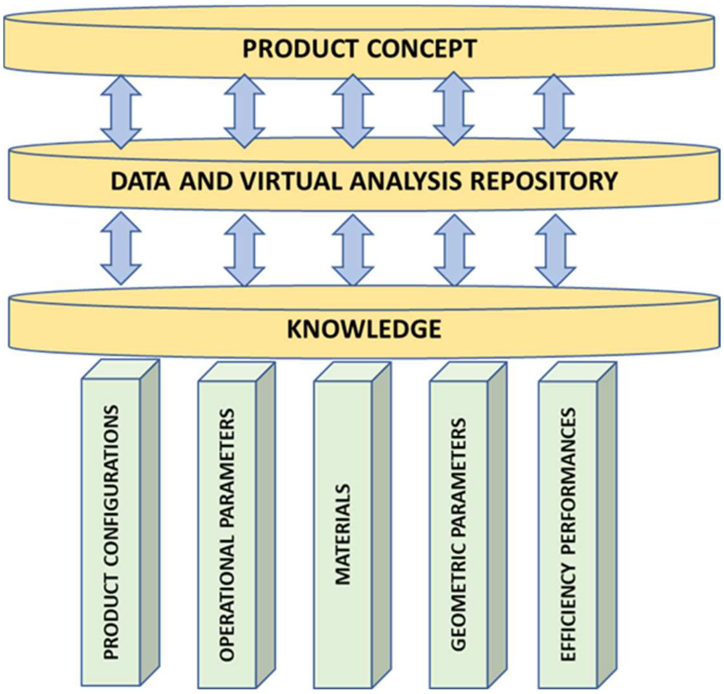


Figure 28 - Virtual analysis repository

The effect of the database is that, during the design or the re-design process, the product, starting from initial requirements, has some features improved from studies that constitute the database. In this way, designers can choose or evaluate possible improvement and modification about the product to improve its environmental performances. The performances of the final product, by consulting database, can be superior to that of the starting points without the possibility of the virtual analysis support.

In this section by consultation of virtual tests, designers can acquire knowledge about:

- Different product configurations (Physical and functional relation of each part, relation between functionality of the product and each part);
- Different operational parameters configurations;
- Different geometric parameters (geometries, shape and sizes);
- Different materials with different properties;
- Influence of different parameters on performances of the product;
- Energy efficiency and energy label test of the product;

At the same time, when new virtual and experimental tests are performed the database can be updated and filled with new knowledge.

5.4 Environmental analysis repository

The influence of conceptual and embodiment design of eco-friendly product is very high. In fact, during these phases, designers can define package, material, functionality and possible recycling strategies of the product. The challenge for the designers is the decision complexity, they need a lot of eco-related information of the product.

The decision-making process for designers within an early phases of product development phase can be supported by many data and information from previous environmental product analysis. During the design process with an environmental point of view, the designers has to make an upgrade in decision making and information. The possibility of consult environmental analysis is a good basis of the decision support.

The possibility to collect environmental knowledge on assembly, disassembly, materials…can be relevant to support the use of eco-knowledge in decision making. The complexity of decision for the designer can be simplified if he knows CO2 emissions, disassembly procedures, reliability information about the product.

Designers can access form database to life cycle analysis and environmental loads such as CO_2 emissions of the product and parts. In this way, the designer can understand previously if a part generates high CO_2 emissions and can upgrade it for low cost and CO_2 emissions.

In particular, the guidance coming from the eco-knowledge represented by environmental analysis, related to specific product or component, will result useful to optimize the product functionalities, in environmental terms to obtain the best product behaviour and its total correspondence to the fixed requirements (Figure 29).

Environmental analysis can come from past internal studies, studies realized by external consultants, regulations related to the use of materials, internal regulations of company, etc.

Starting from these results, the designer involved can select the most representative knowledge and also can store the new knowledge created during the design process or when the product is completed in compliance with the structure of the database.

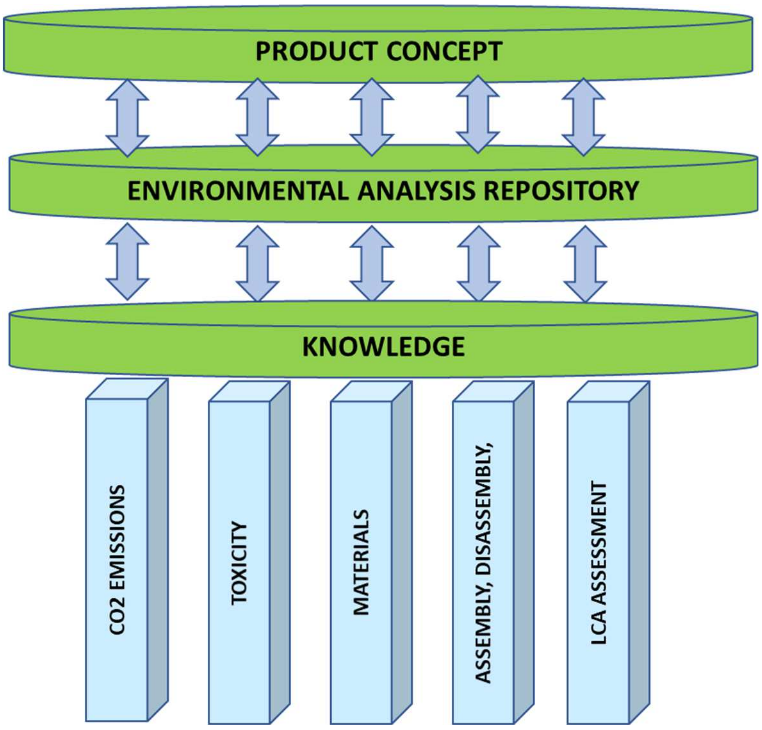


Figure 29 - Environmental analysis repository

Chapter 6.

Application of the V.E. Approach in real industry case study

6.1 Hypothesis and experimental program

In the previous chapters, we described the proposed solution associating an eco-design methodology with an engineering traditional design process. This chapter presents the case study realized in order to test and validate the proposal.

The Virtual Eco-Design approach have been tested to support the activities of design departments in the product design and re-design oriented to sustainability. To validate our solution, we need to verify the satisfaction of the four functions recognized by the methodology and satisfied by V.E. database:

- ***Integration:*** integration of environmental dimension in the product designers' activities
- ***Eco-knowledge creation***: creation of company knowledge that collects information to develop new design concepts;
- ***Analysis of performances***: analysis of the energy performances and use phase using virtual models;
- ***Decision-making support***: support the decision-making process to choose the most satisfying possible solution;

An International company, whose name is omitted for confidentiality reasons, and Electrolux S.p.A. have been involved in this work programme with the purpose to verify the quality and the level of penetration reached by the introduction of this methodology. Companies involved in this test campaign are important firms in the context of production of household appliances.

In this research thesis, a design of new marketable sustainable product is presented. The design activities have been started considering a standard product already available in the market which has been defined as the current state of the art for the specific product family. The considered product is the induction hob.

The experimentation is focused on the design process of the product and in order to describe the eco-sustainability improvements achieved. The two main phases of the approach are the conceptual design phase and the embodiment design phase, during which the most important part of the experimentation took place and the V.E. database develops its function.

The aim of the experimental program established for this work is to define a set of experiments enabling to get the best validation of the proposal. This program was implemented to test different assumptions.

Experimental Phase n°1: The first experimental phase objective is to validate the four functions of the methodology focusing on the conceptual design phase by consulting the V.E. Database and using the guidelines tool in a company which designs and manufacturers induction hobs. The test phase is carried out in order to illustrate the different steps of methodology and to identify possible problems and weakness in our approach. In the corresponding section, the description of the guideline tool is presented and the construction and consultation of it.

Experimental Phase n°2: The second phase aims also at validating the four functions of methodology focusing on the consultation of database during the embodiment phase and the support to the design activities and investigation of performances through the virtual model. In the corresponding description section there is the description of development of the virtual model and the different configuration analysed. The test of the methodology aims to validate its robustness in each step of the product design.

6.2 The product case study

6.2.1 The description of the product: induction hob

The induction hob is an industrial product which is subjected to the European Directive for the reduction of the energy consumption.

Induction cooking delivers heat to the pan using a strong magnetic field created under the ceramic plate. This field generates an induction current which produces heat that is drawn upwards in to ferrous type pans.

The field source is represented by the inductor that consists of a copper Litz wire forming a planar Archimedean spiral winding. As the operation frequency is in the range of 20–100 kHz, the field generated by the inductor is mainly magnetic, and this allows us to neglect the effect of the cooking surface and electric insulation, because negligible conduction currents are induced in these materials by the external magnetic field.

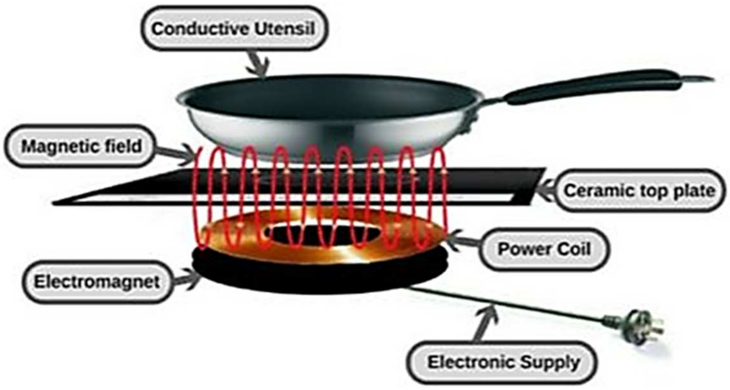


Figure 30 - Induction hob

According to Faraday's law, the alternating magnetic field induces eddy currents in the metal pan, and additionally, ferromagnetic material produces magnetic hysteresis, both phenomena heat up the load. The heat generated in the pan is transferred by conduction to the glass through a thermal contact conductance, which includes the imperfect contact between both surfaces due to the intrinsic rugosity of the materials. There are losses to the environment on the top surface of the bottom, the disk border, and the glass due to the convection and radiation.

The temperature reached inside the bottom of a pan during the heating is the consequence of the heating source and the power transmission.

The induction process heats the pan instantly, which then passes the heat on to the food it contains. This is more efficient, as most of the heat generated is transferred directly to the food thereby reducing cooking times, whereas with conventional gas and electric cooking more of the heat is wasted. When a pan is lifted off the induction hob, heating stops straight away, and the hob is switched off automatically, saving energy and improving safety.

The induction hob is redesigned with the purpose to test, in a real design process, the improvements carried out with the eco-design implementation during the design process.

Figure 31 - Operational phase and internal components of induction hob

6.2.2 Functional and modular analysis of induction hob

The induction hob has been analysed at first by means of a functional and modular analysis. Using the well know technique of the “black box” model and heuristic-based flow proposed by Stone et al., it is possible to define the modules and the in/out flows (Stone et al.,2000). The overall black box function is to “cook food” and it is broken into other subfunctions (Figure 32). By this division, it possible determine the specific properties of the product and to identify the technical and the functional aspects.

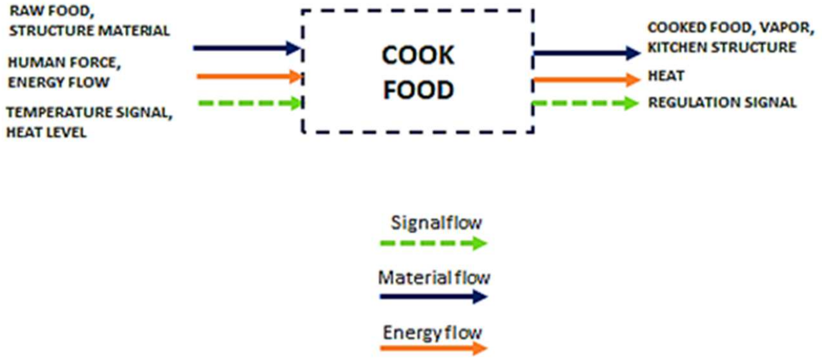


Figure 32 - "Black box" function: Cook food

The functional analysis has general validity for this product and can be repeated for other models of the same product. The “dominant flow” approach is used in this case study for the in/out flow identification.

The result of the functional analysis is presented in (Figure 33).

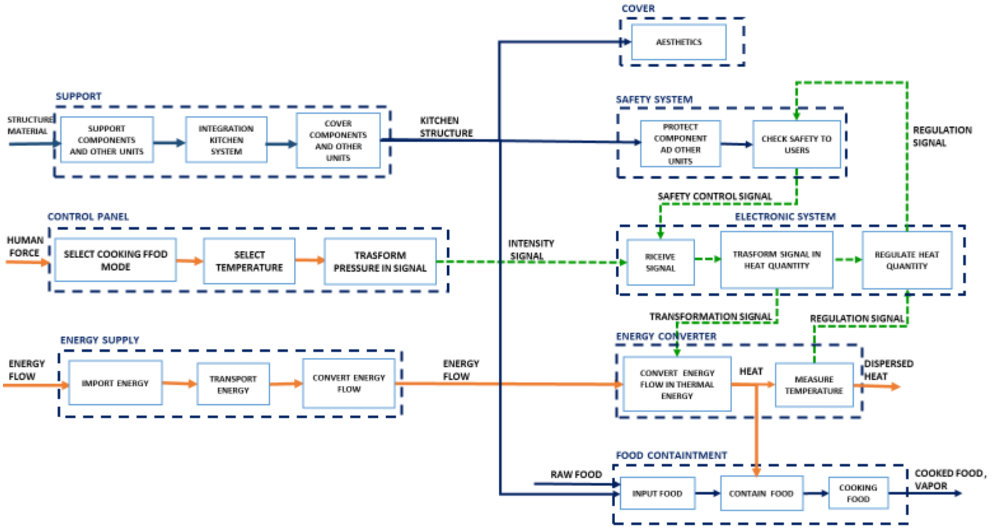


Figure 33 - Induction hob functional and modular analysis

The product is characterized by seven modules; each of them collects some functions:

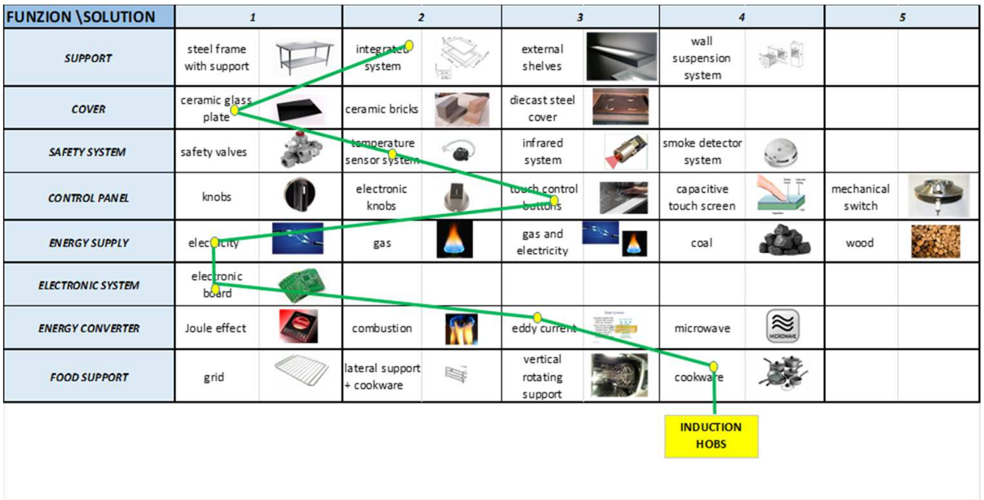
- ***Support***: it represents all the components that have the role to support the hob and other components of it. The input of this module is the structure material, and the output is the kitchen structure which supports the components. This module collects three different functions:
    - Support components and other units;
    - Integration kitchen system;
    - Cover components and other units;
- ***Control panel:*** this module represents the user interface which allows users to view and select the different hob settings. The human force is the input of this module. In fact, the pressure applied by the user is the direct input to choose the cooking food mode. It collects three different functions:
    - Select cooking food mode;
    - Select temperature;
    - Transform pressure in signal;
- ***Energy supply:*** this module represents the equipment that provides and distributes energy to the components; input and output are represented by energy flow taken by network. It collects three different functions:
    - Import energy;
    - Transport energy;
    - Convert energy flow;
- ***Cover***: it represents all the components that have the role to cover the internal element of the hob; It collects one function:
    - Aesthetics;

- ***Safety System:*** it represents all the components that have the role to ensure the safety of the hob; It collects two functions:
    - Protect component and other units;
    - Check safety to users;

- Electronic System: this module represents the equipment that provide the transformation of the signal into heat quantity. It collects three functions:
    - Receive signal;
    - Transform signal in heat quantity;
    - Regulate heat quantity;
- Energy Converter: this module represents the equipment that provide the transformation of the energy taken from the network into the thermal energy; it collects two functions:
    - Convert energy flow in thermal energy;
    - Measure temperature;

The product is completely modular with a unitary degree of modularity. The transition from product modules to potential design solutions is based on the knowledge of specific properties identified during the generation of the product modules. A very helpful tool at this step is the morphological matrix which can improve the effectiveness of the conceptual analysis and translates functional modules to physical modules. A morphological matrix is traditionally created by labelling each line with all the identified product modules and, for each module, the possible design options, listing the solutions as columns and the product module as rows. The morphological matrix finally shows existing alternative design options for each functional module of complex system and it permit a rapid configuration of the product with the selection of the best option for each specific module.

In this case the morphological matrix is the following (Figure 34):



FUNZION \SOLUTION	1	2	3	4	5
SUPPORT	steel frame with support	integrated system	external shelves	wall suspension system	
COVER	ceramic glass plate	ceramic bricks	diecast steel cover		
SAFETY SYSTEM	safety valves	temperature sensor system	infrared system	smoke detector system	
CONTROL PANEL	knobs	electronic knobs	touch control buttons	capacitive touch screen	mechanical switch
ENERGY SUPPLY	electricity	gas	gas and electricity	coal	wood
ELECTRONIC SYSTEM	electronic board				
ENERGY CONVERTER	Joule effect	combustion	eddy current	microwave	
FOOD SUPPORT	grid	lateral support + cookware	vertical rotating support	cookware	

Figure 34 - Morphological matrix

Using the morphological matrix, it is possible to recognize different types of products. An induction hob has been recognized from the morphological matrix and is the analysed case study of this work.

The induction hob is a complex system and on the basis of the functional analysis and the modular approach several product modules have been identified in the conceptual design stage.

An example of possible design solution proposed by the morphological matrix for each module of induction hob is following:

- ***Support:*** Integrated System,
- ***Control panel***: Touch Control Buttons;
- ***Energy supply***: Electricity;
- ***Cover:*** Ceramic Glass Plate;
- ***Safety System***: Temperature Sensor System;
- ***Electronic System***: Electronic board;
- ***Energy Converter***: Eddy Current;

In the conceptual design phase, there is the product module definition and the classification of the design solutions, and are available only general information and not specific details about geometry, shape, manufacturing parameters, material designation, etc.

Based on the V.E. approach, different design solutions will be pointed out as design solutions. The different design solution will be chosen by the designer following the environmental ranking in the guideline tool present in the V.E. Database.

6.3 Regulations concerning the performance: EN 60350-2 standard—Household Electric Cooking Appliances—Part 2: Hobs—Method for Measuring Performance

The *EN 60350-2 standard—Household Electric Cooking Appliances—Part 2: Hobs—Method for Measuring Performance* defines methods and parameters for measuring the performance of electric hobs for household use.

The energy consumption measurement of the induction hob 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. Tests is carried out in a substantially draught-free room in which the ambient conditions were maintained at 20°C ± 5°C, while the relative humidity measured was 50%rh. The supply voltage shall be maintained at the main terminal at 230 V ± 1% or at 400V ± 1% as defined by manufacturer's installation guide, when the heating elements are switched on. The supply frequency shall be at a nominal 50 Hz ± 1%. The absolute air pressure shall be 913 hPa to 1063 hPa. The water had a temperature of 15°C ± 0.5°C. the cookware covered with the lid is positioned centrically on the cooking zone or cooking area. Standardized cookware with lid specified dimensions are used, and each hole on the whole circle of the lid had a diameter of 16 mm ± 0.1mm. the holes are distributed on the whole circle and in the center of the lid there is the accommodation of a temperature sensor, which is positioned 15 mm above the inner cookware bottom.

The test follows three times to be followed (Figure 35):

(i) heating up period, when water is heated from 15°C to 90°C

(ii) switch-off for overshoot period, when water is heated from 15°C to 70°C and overshoot is determined for determination of the Tc

(iii) switch-off max power time, when maximum power is switched to reduced power that enables simmering.

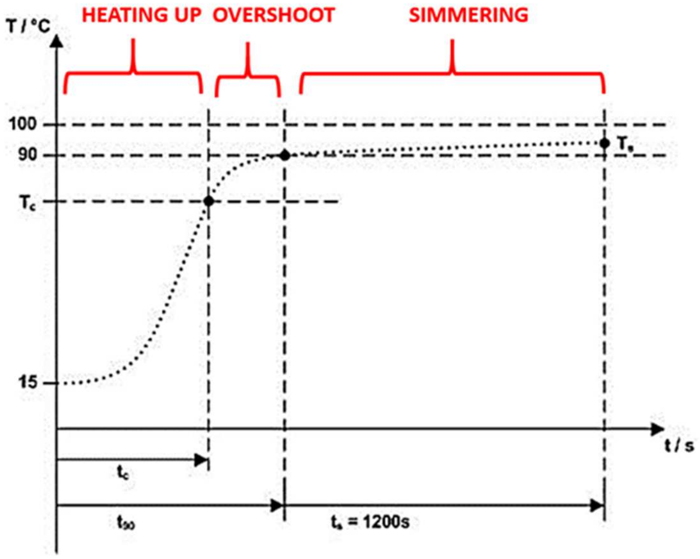


Figure 35 - Periods of energy consumption test

During the measurement of hob performance, switch-off for overshoot time and Tc have to be determined in advance.

According with the standard, preliminary tests have to be carried out to determine the appropriate water temperature (Tc) for reducing the power setting and to determine the lowest power level set to achieve ≥90°C during the remaining cooking period. The power shall be switched off when the water temperature reaches 70°C. The highest temperature value was stated as the temperature overshoot (ΔT_0).

The temperature Tc (Figure 36) was calculated from the overshoot according to

$$T_c = 93°C - \Delta T_0$$

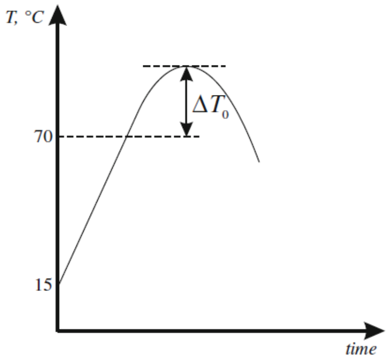


Figure 36 - Calculation of the Tc temperature

During the heating up period, the cooking zone was heated with the maximum power and when Tc is reached during the energy efficiency measurement, the power setting is reduced from the maximum to achieve water simmering at a temperature ≥90°C and as close as possible to 90°C. When the water temperature reached t_{90} = 90°C for the first time, the simmering time (t_s) started independently from Tc. 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 consumption E_{hob} shall not be greater than the value declared by the manufacturer plus 10% plus 0.015 kWh. For example, if a manufacturer declares that the energy consumption of an appliance is 0.200kWh, then the measured value shall be less than 0.235kWh.

Parameter	Unit	Minimum resolution	Minimum accuracy	Additional requirements
Instruments				
Mass	g	0.5 g	< 1000g ± 1g	
Ambient temperature	°C	0.1 °C	> 1000g ± 3g	
Temperature, water load	°C	0.1°C	± 1 K	
Time	s	1s	± 0.5 K	
Energy	Wh	-	± 1 s	
Air pressure	hPa	1 hPa	± 1 %	
Measurements				
Voltage	V	-	± 0.5 %	
Temperature and energy consumption measurement		-	-	Sampling rate < 1 s (digital measurement data)

Table 5 - Instruments and measurements required by the standards

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.

6.4 Experimental Phase n° 1

6.4.1 Objectives and research questions

The first experimentation aims to validate that the methodology facilitates the identification of the environmental hot spots and the development of ecodesigned products since the early phase of product design through the satisfaction of the four functions of the methodology (integration, knowledge creation, decision making support, analysis of performances).

The objective of this experiment is also to illustrate the valid support of database in the redesign of the induction hob and to show the changes in the design process involved by the implementation of the methodology.

During this phase after the definition of the methodology and the development of the guideline tool in a prototype version, the experimentation to test and validated the tool started.

The research questions of the experimentation are:

- Can eco-design value guidelines be used as eco-criteria in qualitative eco-evaluation of products concepts?
- Which are possible factors that may influence the qualitative eco-evaluation of product concepts?

Guidelines tool consist of a number of design principles that are potentially guidelines for establishing design strategies from the ecological point of view and can be used for evaluation purposes.

The experimentation was performed to explore the influence of ecodesign guidelines when used as eco-criteria in the product concept eco-evaluation. The goal was to investigate the value of utilizing guidelines as criteria of environmental friendliness of the decision taken during the conceptual phase.

6.4.2 Stages of experimentation

Implementing a new procedure is often long and difficult process and integrating environmental consideration in the design process since the conceptual phase is part of this. The experimentation of the tool was organized in two stages.

I. Evaluation of guidelines applicability
II. Evaluation of usability/effectiveness and customization

Evaluation of guidelines applicability

In the first stage designers involved in the experiment were not informed about eco-design issues. In this phase, the tool was implemented with only the section related to eco-design guidelines filled in and classified by the eco-design score (the qualitative evaluation based on three criteria), due to the fact that designers do not have specific knowledge related to environmental sustainability.

For this reason, the tool was tested to only evaluate the *applicability* of eco-design guidelines to different product modules. The *applicability* of guidelines was evaluated in the specific section of the tool using the evaluation grid of the *applicability score*.

Applicability score, in this phase, is an important instrument to evaluate the real role of the guidelines in the design process of a company. Through this score, designer can establish the influence and the applicability of the environmental suggestion in the real design dimension.

The human resources involved in this phase were two designers with a long experience in the household appliances design but without skills on environmental issues. They were accustomed to evaluating concepts on the base on their personal experience. The designer evaluators were asked to estimate if eco-design guidelines are potentially realizable on product concepts. When the applicability score for the guidelines are assigned, the guidelines with the highest ecodesign score could be the one with the lowest applicability score. On the other hand, the ranking with a high applicability score can demonstrate the applicability of the eco-design without conflicts.

This phase has been realized into 1 month.

Evaluation of effectiveness/usability and customization

This second stage of experimentation is based on the evaluation of the *effectiveness/usability* and the *customization* of the tool.

During this phase the tool was provided with only eco-design guidelines retrieved from literature and then in the customization phase designers, has added specific guidelines and knowledge in the dedicated section of the database.

The objectives reached during the test were the evaluation of the effectiveness of the tool during a design/redesign project, both in improving designers' knowledge on eco-sustainability issues and in supporting the problem-solving process and the evaluation of the tool usability.

The resources involved in this test phase were four:

- *An expert designer with environmental skills:* The user is a Mechanical Design Engineer (PhD in Environmental Engineering), 35 years old. He has been recruited by company as a lab engineer with ecodesign skills. He is involved in innovation product projects and has a strong know-how in eco-design and in environmental sciences because of his previous research experiences in the fields.
- *An expert designer without environmental skills*: The user is a Mechanical Engineer and Designer (Master Degree), 36 years old. Recruited by company as a mechanical engineer. He has no know-how in eco-design.
- A young designer without experience: The user is a junior mechanical engineer (Bachelor Degree), 25 years old. He has been recruited by company as a lab engineer. He is involved in the training activities about product design.
- *A young designer with environmental skills*: The user is junior mechanical engineer (Bachelor Degree), 26 years old. He has been recruited by

company as designer and is fully involved in innovative product development. he has a basic know-how in eco-design and in environmental sciences.

This stage was organised as following:

- *Evaluation of effectiveness/usability of the tool*: the objective was to clearly evaluate the tool, its interface, its characteristics if it is rapid to be understood during its use. During the use designers acquired knowledge on eco-design, by consulting eco-design guidelines. Then, they derived the main product criticalities, in environmental terms.
- *Customization of the tool:* The designers involved in the test have stored the company knowledge and guidelines into the database. These guidelines have been stored under the specific attribute of company eco-knowledge.

Questionnaires in the Excel Format have been prepared for the evaluation of effectiveness/usability. These questionnaires have been provided to the users after their familiarization with the tool and after the test period of two month.

A total of 44 questions were given, in order to evaluate several tool characteristics, while providing questions simple to be understood and rapid to be answered by the user. Moreover, the possibility to provide an additional feedback has been given to users.

Two different typologies of questions have been defined:

- General, when the user provides an overall opinion on a metric (e.g.When you open the tool, is it clear what steps you can/should perform?)
- Specific, when the user provides an opinion on a specific aspect. (e.g. Is it the tool aesthetically pleasing to the user?)

Question have been grouped into different aspects: “Compatibility”, “Consistency and standards”, “Explicitness”, “Flexibility and Control”, “Functionality”, “Informative Feedback”, “Language and Content”, “Navigation”, “User guidance and Support”, “Visual Clarity Description”, “Impact on the traditional design process”, “Personnel to involve if the tool will be implemented inside the company”.

This approach has been chosen to obtain some general opinions about the tool. This allows the software developers to understand if globally the tool satisfies the user expectations or not.

Each question has five possible options (sufficient, satisfactory, good, very good, excellent), ranking the tool usability and effectiveness. The following ranking criteria have been chosen for the quantification of user's opinions:

- Sufficient (score=1);
- Satisfactory (score = 2);
- Good (score = 3);
- Very Good (score = 4);
- Excellent (score = 5);

The scores given by the users for each question have been summarized in a single value. In accordance with the software developer experience and with the company involved in the test, each aspect has the same weight so it possible to evaluate it using the arithmetic mean of the questions. The formula used for this evaluation is defined in equation:

$$AM = \frac{1}{n}\sum_{i=1}^{n} a_i = \frac{a_1 + a_2 + \cdots + a_n}{n}$$

where n is the numbers of questions, a_i is the score of each question and the general evaluation of each aspect is the arithmetic mean of a_s divided by *n.*

Users have taken a medium period of one week to compile the questionnaire. The analysis of results and involved one person for 4 days.

6.4.3 Application on the case study

The selection of the concept, or the principal solution, provides the basis for starting the embodiment design phase. The large number of variants has to be reduced to one concept, or just a few, to be pursued further. The aim of the conceptual phase is to focus on those working principles, components or parts of the structure that are essential for the evaluation of the concepts and the selection of the one that will be transferred to the embodiment stage.

After the identification of the different modules of the product and the design solutions, the designer consults the database and the related tool to know the guidelines.

Figure 37 - Example of consultation of guidelines database

Some examples of consultation of V.E. Database are following:

Example:

Product: Induction Hob

Product Module: Energy Converter

Filter:

- *Category*: Energy Consumption;
- *Interested Design Phase:* Embodiment;
- *Source:* From literature;
- *User:* Mechanical Engineer;

Guidelines:

- *"Use the lowest energy consuming components available on the market";*
  Ecodesign Score (E.S.): 9 (Sustainability Dimension (3) – Process Design Phase (3)- Lifecycle (4));

- *"Coil elements must be well insulated to avoid losses"*; ***Ecodesign Score (E.S.)***: 8 (Sustainability Dimension (3) – Process Design Phase (2)- Lifecycle (3));

- *"Insert an automatic switch off system if the pan is removed in order to save energy"; **Ecodesign Score (E.S.):*** 7 (Sustainability Dimension (2) – Process Design Phase (2)- Lifecycle (3));

Example:

Product: Induction Hob

Product Module: Cover

Filter:

- *Category*: Design;
- *Interested Design Phase:* Embodiment;
- *Source:* From literature;
- *User:* Mechanical Engineer;

Guidelines:

- "*Apply visual elements and information encouraging environmental consciousness of the product"; **Ecodesign Score (E.S.):*** 8 (Sustainability Dimension (3) – Process Design Phase (2)- Lifecycle (3));

- *"Specify correct position of the pan on the glass ceramic top to avoid energy consumption"*; ***Ecodesign Score (E.S.):*** 8 (Sustainability Dimension (3) – Process Design Phase (2)- Lifecycle (3));

- *"Provide a good arrangement of the part in the assembly of product to avoid additional material"; **Ecodesign Score (E.S.):*** 7 (Sustainability Dimension (2) – Process Design Phase (2)- Lifecycle (3));

6.4.4 Results of Experimentation

Evaluation of guidelines applicability

After the implementation of the tool, guidelines applicability has been evaluated. Each guideline present in the database has been evaluated by users using the applicability score. In this phase users were designers with experience without environmental issues. Questionnaires with open question have been prepared for this evaluation. A critical analysis of the answers has been performed to formulate the evaluation.

The list of 162 guidelines and their evaluation has been reviewed and validated by design experts and we have received our feedback on the guideline tool from users. Guidelines formalize rules to apply in the design of more environmental-friendly products.

During this phase of evaluation, it was noticed that the guidance of environmentally ranked guidelines during the design process was crucial to maximize the positive outcomes of using the tool. The eco-design score of guidelines could give a quick and general introduction to the concept of sustainability in the product development process. While users evaluated the applicability of guidelines, they at the same time could acquire important background information about sustainability aspects.

The main results of this evaluation can be summarized as follow:

- The guidelines collected in the database are both generic and specific and show a relevance in the design for different purpose.
- The attributes of guidelines provided to help designers filter them, depending on the objective they want to reach and focus on a shortened, relevant list.
- The evaluation of guidelines applicability shows:
    - 30 guidelines have been evaluated with an applicability score comprised among 8 and 10;

- 51 guidelines have been evaluated with an applicability score comprised among 7 and 5;
- 40 guidelines have been evaluated with an applicability score comprised among 3 and 4;
- 26 guidelines have been evaluated with an applicability score comprised among 1 and 2;
- 15 guidelines have been evaluated with an applicability score of 0;

Results of evaluation of usability/effectiveness.

As already explained, the tool has been evaluated in terms of effectiveness/usability, due to the fact there were guidelines retrieved from literature stored in the database. In the following table the main results obtained are presented:

Aspects to Evaluate	***Evaluation***
Compatibility	3
Consistency and standards	4
Explicitness	3
Flexibility and Control	4
Functionality	3
Informative Feedback	3
Language and Content	3.5
Navigation	4
User guidance and support	3
Visual Clarity Description	3.5
Impact on the traditional design process	3.5
Personnel to involve if the tool will be implemented inside the company	3.5

Table 6 - Results of evaluation of usability/effects

The evaluation of the usability has provided interesting results, with opinions poising between “good” and “very good”. The tool has been positively evaluated by the user in performing its functions. The most appreciated aspects were:

- Filtering in consulting guidelines;
- Simplicity of structure of the tool functions;
- Clarity of navigation;

On the contrary, the aspects which have obtained the lowest values were the about the syntax of the guidelines and the user guidance and support. The guidelines are gathered with the aim of completeness, but sometimes the syntax appears difficult to understand at first read and guidelines could be simpler in order to avoid redundancies in the information. The idea is to make the guideline more concise and add further section with deep information. A possible improvement of the tool on the user guidance and support is the possibility to consult a tutorial in a section of the database in order to avoid an initial training session with a developer and make the user completely autonomous in the use.

Also, the results obtained in the evaluation of tool effectiveness and usability within the company appear satisfactory. To facilitate the usability of the tool a possible solution could be a graphic improvement with specific symbols, colours and icons to simplify the role of guideline. The tool provides results that can effectively support the designer work, and in the integration in the design process, it appears as useful tool to facilitate decisions and reduce the time analysis. The tool has been evaluated as usable without specific knowledge, admissible and compatible with the standard time of the traditional design process.

Results of customization of tool

The customization of the tool by company and designers have been carried out in the final time of experimentations. Users added 13 specific company guidelines to the database, and they have organized them following the attribute structure of the tool. In fact, before customization tool was conceived as a universal tool for different company and different products. For a company focus on a single product or on a limited family product could be an important simplification. In fact, the possibility to dispose of a repository of specific company knowledge reduce the time during the design process and increase the awareness of designers. As concerns suggestions on how to improve the tool, users indicated the possibility to add other specific criteria to filter and organise guidelines. Through the addition of company-specific criteria, designers can better link guidelines to their realities. Another aspect can be considered to improve the tool functionalities and customization such as giving the possibility to the user to select with a check the guidelines he has consulted and/or applied on the product.

6.4.5 Discussion

This experimentation shows the usefulness of guidelines tool as support to the design process and a further research could be the measurement of the improvement that guidelines can make. The tool appears very adaptable to company's need, nevertheless, some modifications are needed to facilitate the customization.

Further study can be focused on making tool able to self-evaluate the applicability of the guidelines without requiring evaluation by the user as it is used by the company.

Finally, whereas guidelines tool is recognized as a useful design tool for a company, possible studies can be based on analysing and testing the ability of the tool to contribute to the environmental awareness in product design performing specific analysis on the products.

6.5 Experimental Phase n° 2

6.5.1 Objectives and research questions

In this phase of experimentation, the objective is to validate the four function of methodology focusing the attention on the consultation of V.E. Database during the Embodiment phase of design process when the product concept gets concrete forms and the result is a layout in accordance with technical and economic criteria. The research questions of the experimentation are:

- Can virtual prototyping be used as tool in performance evaluation of products?
- Which are possible factors that may influence performance evaluation of product since the design phase?

Answering these answers, the construction of the definitive layout of the product, with the support of the V.E. database, took place in this phase of the methodology. This phase of the experimentation highlights the importance of the development of the virtual model in order to study and to improve the product since the design phases.

6.5.2 Development of the Virtual Prototypes

The approach presented in this thesis aims to develop a methodology to support design during life cycle of the product. The approach is based on the development of a flexible method based on virtual prototyping tools which are able to simulate performances and operative principle of the product. The followed approach is generic and can be applied to support design of different products, in particular household appliances considering estimation of the energy efficiency and performances evaluated in accordance with eco-design regulation required by European commission. Semantically, a virtual model consists of one or more than one component governed by its own principles for evolution or equilibrium, typically conservation or constitutive laws and need of the development of specific methodology to have a coherent model.

6.5.3 Application on the case study

In this case study, the induction hobs are a category of products involved in the Eco-design Directives. The operative principle of induction cookers is multi-physics and requires a physical and numerical modeling of the problems.

The virtual models of the product are collected in the V.E. Database in order to be consulted by designers during the design process. Virtual models provide information about materials, operational phase of the product, energy consumption, configuration parameters etc.

Figure 38 - Examples of consultation of virtual prototypes database

Multiphysics methodology

The methodological approach described in this section is implemented in order to lead the modelling of a virtual prototype which reproduces the multi-physics behaviour of an induction hob (

Figure 39). The currents that heat the material are induced by means of electromagnetic induction in a non-contact heating process, and by applying a high frequency alternating current to an induction coil, a time varying magnetic field is generated. The alternative electromagnetic field induces eddy currents in the workpiece, resulting in thermal losses, which then heat the material.

The first methodological phase concerns the definition of input such as technical input of induction hob, the performance, the customer requirements, the necessity to obtain good performances and the features of the product.

The second phase regards the definition of a 3D CAD model which is the starting point of the methodology. According to the inputs, the 3D model represents the functional model to analyze.

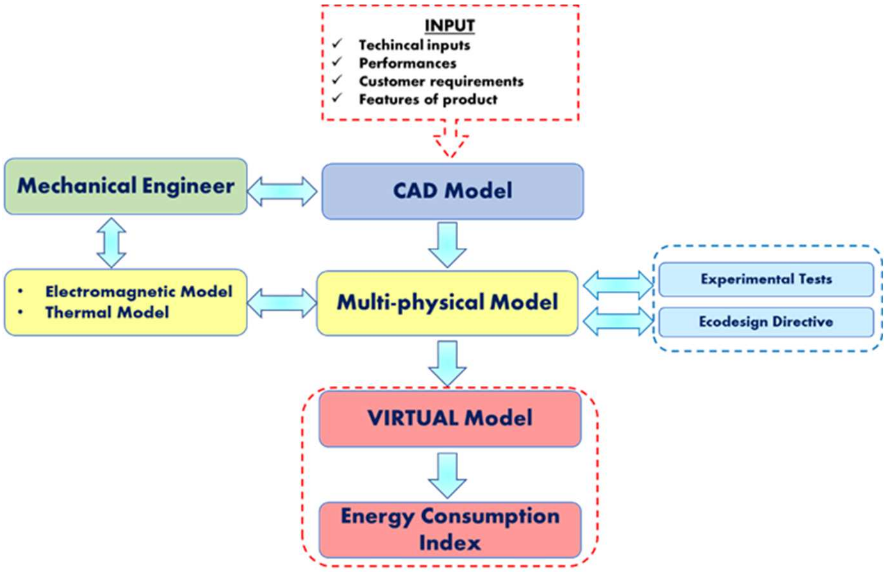


Figure 39- Multiphysical Methodology

The third phase is represented by multi-physical modelling which allow to simulate the electromagnetic and thermos fluid dynamics behavior of induction hob using FEM and CFD tools.

The electromagnetic model solves the equations of Maxwell (FEM tools), while the thermal model solves the thermodynamics classical equations (CFD tools). In the multi-physical model, the output obtained by the electromagnetic model is the input to the thermal one. Depending on the current and frequency that passes in the copper coil, it is possible to evaluate the eddy currents generated on the bottom of the pot and the relative heat generated by the Joule effect. The heat which is obtained through the electromagnetic model is an input to the thermal module and is able to simulate the fluid-dynamic behavior of the product.

The fourth phase concerns the definition and the formalization of the virtual prototype, which is the numerical model used to simulate all operating conditions and to evaluate performances both in test condition and other situations. For example, the output ohmic losses of electromagnetic model, depends on current and frequency, but also on geometry of the coil and of the workpiece, consequently, this output ohmic losses influences the thermal and fluid-dynamics aspects.

The virtual model contains several information about the product and allows to reproduce the operational phase in compliance with the Directive. In order to assess the correctness of the model, experimental tests are necessary. The experimental tests are carried out following the testing procedure regulated by directive, identifying the main outputs and inputs of the system, but the feasibility of the models allows to evaluate conditions different from the test ones.

The last step of the methodology is the comparison between the numerical model and the experimental tests in order to evaluate the error. In this phase the role of designer is very important for the analysis of the product performances compared to the design values. The methodology is flexible and can be applied to different types of product whose operational phase is multiphysics, not only to induction hobs. The final result of these different steps is the evaluation of the energy efficiency of the product through the virtual model, since the design phases and overcoming the need of experimental tests.

6.5.4 Simulation and modelling of Induction hob

CAD Model

The development of the model starts from the real product, taking into account characteristics and features of product available on market.

The system (

Figure 40) comprises:

- the pot;
- a cooking surface realized in glass ceramic material;
- a layer of electric insulation material consisting in a sheet of mica;
- an inductor coil to generate the magnetic field;
- 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);
- water;

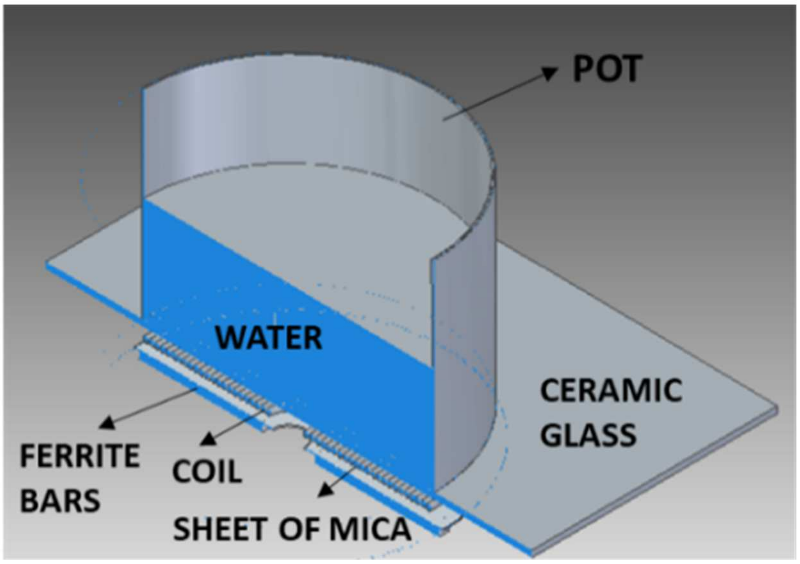


Figure 40 - CAD Model

In this study, the system consisting of the induction cooker has been modelled in each part with the support of a CAD tool, following the faithful reproduction in features, size and material of the actual physical prototype. In general, the solid model should be simplified as much as possible before transferring to the tool, this simplification may include suppressing extraneous features as well removing components that are not needed in the analysis (e.g. all the screws present in the assembly model, components that are not included in the analysis zone, several structures not influencing the system). The simplification is necessary to spare computational power and time of simulation.

Simplifications considered in the CAD model:

- The Litz wire is simplified as a cylindric wire of the same diameter;
- The mica insulation is not considered in the electromagnetic simulation because not fluent on the electromagnetic behaviour;
- The ferrite bars are considered in a radial position as in the real product;
- The coil is considered as a closed computational volume closed at the extremity;
- The pot considered a cave cylinder without handles and conform to the European standard requirements;
- The amount of water is considered as a defined volume in the pot in the thermal analysis with multiphase properties following the European standard requirements (EN 60350-2);
- The water is not considered in the electromagnetic analysis because not influent in the generation of ohmic losses;
- The volume of air is considered as a box cube around the model;
- The distances in the model are fixed starting from the real product;

After the modelling of the geometry, it is necessary to assign materials to each part of the assembly.

Multi-physical model

The Multiphysics virtual model is composed by a virtual analysis of the electromagnetic phenomenal and of thermal aspects. The electromagnetic simulation allows 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. For accurate FEM and CFD analysis, the system is discretized in a grid made up of finite element in coded form. The quality of the mesh has a significant impact on the accuracy of the numerical solution.

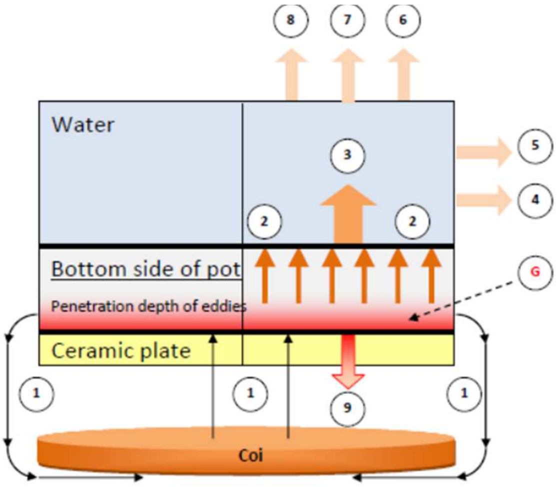


Figure 41 - Operative principles and contributes of heat transfer

The

Figure 41 represents the operative principles and the different contributes of heat transfer of the induction hob system.

- G= heat generator (a metal layout from external side of the pot can be considered);
- 1= magnetic flux generated by coil that crosses the bottom side of the pot;
- 2= heat transfer by conduction between the hot layer from the bottom side of the pot (the heat generator) through metal;
- 3= heat transfer by convection from the bottom side of the pot to water;

- 4= heat loss by convection from external surface of the pot;
- 5= heat loss by radiation from external surface of the pot;
- 6= heat loss by convection from external surface of the lid;
- 7= heat loss by radiation from external surface of the lid;
- 8= heat loss by vaporization of the water;
- 9= heat loss by conduction through the bottom side of the pot and ceramic plate;

Electromagnetic model

The objective of the electromagnetic model, analyzed using a FEM tool, is the simulation of eddy current phenomenon and the consequent Joule effect on the pot, which represents the load of the system. The electromagnetic model is classically based on the set of Maxwell equations. This system is based on the following equations:

- Magnetic flux equation $\vec{\nabla} \cdot \vec{B} = 0$
- Maxwell-Gauss equation $\vec{\nabla} \cdot \vec{E} = 0$
- Maxwell-Faraday equation $\vec{\nabla} \cdot \vec{E} = -\frac{\overrightarrow{\partial B}}{\partial t}$
- Maxwell-Ampere equation $\vec{\nabla} \times \vec{H} = J + \frac{\overrightarrow{\partial D}}{\partial t}$

where $\vec{H}$ denotes the magnetic field, $\vec{B}$ the magnetic induction, $\vec{E}$ the electric field, $\vec{D}$ the electric flux density, $\vec{J}$ the electric current density associated with free charges. The following relations are for the intrinsic material properties:

- $\vec{D} = \varepsilon \vec{E}$
- $\vec{B} = \mu_m(T, |\vec{H}|)\vec{H}$

and the Ohm law is: $\vec{J} = \sigma(T)\vec{E}$

where ε is the dielectric constant, μ_m the magnetic permeability, and σ the electrical conductivity. When dealing with low or medium frequencies, it is possible to neglect the displacement currents in the Maxwell-Ampere equation (magneto-quasi static approximation).

Thermal model

The aim of the thermal model is investigating the heat exchange and temperature distribution on the system, in order to analyze trend of temperature and energy consumption in accordance with the normative. The value of the power produced at the bottom of the pot, is estimated in the electromagnetic model, this value is the input of the thermal one.

In general, there are two methods of simulating heat, mass transfer and flow of the fluid in CFD: the first method is a single-phase method with effective physical properties such as thermal conductivity, heat capacity, density and viscosity of a composite fluid representing the characteristics of the fluid in bulk. The second method is a two (or multi-) phase approach, which defines the first phase as a fluid and the second phase as a fluid cloud of particles (solid). The two-phase model is found in literature to provide improved predictions over the single-phase model; as such the two-phase method with Eulerian-Eulerian approach is applied in this work. This approach assumes that at least two fluids are continuously penetrating each other. The volume fraction of the fluids in each cell sums to unity. For each fluid, the full set of conservation equations is solved. Therefore, each fluid has a different velocity field. The certain morphology of one or the other phase is neglected. This enables the limitation of computational effort to be applied for industrial problems. The information lost by averaging has to be reappear in the closure relations describing the exchange between the phases. The mechanisms of the interaction of the fluids are the momentum transfer between the phase, the mass transfer modelled by phase change and the energy transfer. Mass conservation, momentum and energy conservation equations of the multi-fluid model are represented by the following equations:

$$\frac{\partial \alpha_K \rho_K U_k}{\partial t} + \nabla(\alpha_k \rho_k U_k) = \Gamma_K$$

$$\frac{\partial \alpha_K \rho_K U_k}{\partial t} + \nabla(\alpha_k \rho_k U_k U_k) = -\alpha_k \nabla p_k + \ \alpha_k \rho_k g + \nabla \alpha_k (\tau^v + \tau_k^t) + U_{k,i}\Gamma_k + M_{i,k} - \Delta\alpha_k \cdot \tau_i$$

$$\frac{\partial \alpha_K \rho_K H_k}{\partial t} + \nabla(\alpha_k \rho_k H_k \upsilon_k) = -H_{ki}\Gamma_k + \ \alpha_k \frac{D_k}{D_t} \rho_k + \nabla \alpha_k (q^v + q_k^t) + q''_{ki}/\mathrm{L}_s + \Phi_k$$

where the subscript k denotes the phase and i stands for the value at the interface, denotes the length scale at the interface, ρ is the density, *U* is the velocity vector, t is the time, p is the pressure, g is the gravitational acceleration, α is the volume fraction, τ_v is the average viscous shear stress, τ_{st} is the turbulent shear stress) *D* is the interfacial shear stress, $M_{i,k}$ is the mass generation, Γ_k the generalized interfacial drag, q''_{ki} the interfacial heat flux and Φk the interfacial dissipation.

The discretized conservation equations are solved iteratively until convergence. Convergence is reached when changes in solution variables from one iteration to next are negligible, overall property conservation is achieved and quantities of interest have reached steady values. The accuracy of a converged solution is dependent upon: appropriateness and accuracy of physical models, assumptions made, mesh resolution and independence and numerical errors.

In terms of turbulence treatment, the dispersed phase zero equation is used for the dispersed gaseous phases, while the SST k-w approach is used for the liquid phase. One of the advantages of the k-w model over the k-e is the treatment when in low Reynolds numbers for a position close to the wall. The effect of bubbles on the liquid turbulence is considered by additional source terms.

Radiation is an existing phenomenon and, in this study, a surface to surface radiation model were selected. This radiation model's main assumption lies in neglecting all absorption, emission or scattering of radiations and considering only surface to surface radiation to be significant enough. The energy flux leaving a given surface was composed of directly emitted and reflected energy. The reflected energy flux was dependent on the incident energy flux from the surroundings, which then can be expressed in terms of the energy flux leaving all other surfaces. The energy reflected from surface K can be written as:

$$\varepsilon_K \sigma T^4 + \rho_K q_{in.K} = q_{out.K}$$

where ε the emissivity, σ is the coefficient of Stefan Boltzmann, ρ is the density, q is the energy flux and K is the surface.

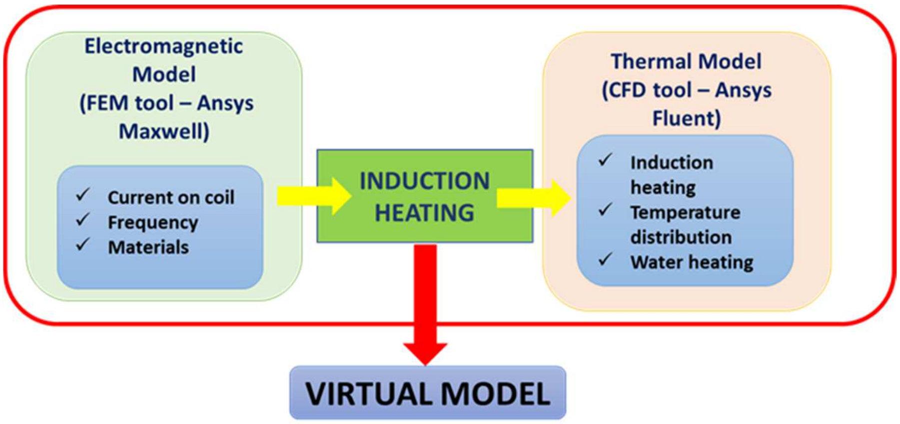


Figure 42 - Inputs and Outputs of the virtual model

The multi-physics approach requires the solution of the electromagnetic and fluid dynamic problems (

Figure 42). The virtual modelling of the induction heating phenomenon is composed by an iterative solution of the time harmonic electromagnetic problem and the transient thermal one. In the electromagnetic analysis, FEM tool is able to estimate the heat flux in bottom of the pot, starting from the input values of current and frequency which feed the coil. The value of the heat flux of the first analysis is necessary as the input for the following thermal one with a CFD tool and for the calculation of the final output such as induction heating, temperature distribution, water heating in energy consumption test.

6.5.5 Objectives of modelling and validation

The aim of this research work is to create a virtual model in order to simulate the performances of an induction hobs. A virtual model should be verified and validated to the degree needed for the reproduction of the intended purpose. The validation of the model is a process that confirms the correct implementation of the assumptions and specification made during its development and checks the accuracy of the representation of the real system. The approach to determine the validity of the virtual model is the comparison with experimental tests. The validation of the model consists comparing outputs from the experimental system to virtual model outputs for the same set of inputs conditions. In this methodological approach, the virtual model aims to be a valid support to study the heating performances and the design of the induction cooker.

During the measurement of hob performance, different parameters have to be determined. The European Standard EN 60350-2:2013 as mentioned in the previous section defines times to be measured:

- heating up period, when water is heated from 15°C to 90°C;
- switch-off for overshoot period, when water is heated from 15°C to 70°C and overshoot is determined for determination of the Tc (preliminary tests were carried out to determine the appropriate water temperature *(T*c*)* for reducing the power setting and to determine the lowest power level set to achieve ≥90 ◦C during the remaining cooking period.)
- switch-off max power time, when maximum power is switched to reduced power that enables simmering when water temperature reaches 90°C for the first time.

The purpose is to assess the energy necessary to heating-up a defined water load (heating up period) and to keep it at a defined temperature level for 20 min (simmering period). Heating up and keeping the temperature for a defined period represent a typical household cooking process. The simmering time of 20 min represents an average household cooking duration.

During this research, in order to validate the virtual models, we performed many measurements on hobs using different cookware and different cooking zones. The model depends on properties and physical magnitudes of both the inductor and the pot, and also on the geometry of the system.

For this reason, the virtual models have been evaluated using different diameters of pot and coils, according to the European Standard EN 60350-2:2013, and a Test Design Matrix have been developed as presented in the following sections.

6.5.6 Experimental Tests: materials, test procedure and Text Design Matrix

Materials

Standardized cookware with lid and water amount as specified are used for the test and reproduced in the virtual models. The material of cookware bottom is stainless steel AISI 430 according to EN 10088-2, the thickness is 6 mm ± 0,05 mm. The surface shall not be shiny. The flatness of the bottom plate is specified for different sizes in the following

Table 7. Convex shaped bottom plate is not allowed, and the cookware is cylindrical without handles or protrusions.

The lid is made of aluminium, thickness is 2 mm ± 0,05 mm. Each hole on the hole circle of the lid has a diameter of 16 mm ± 0,1 mm. The holes shall be evenly distributed on the hole circle. The lid, which is flat, is adapted to accommodate a temperature sensor in the centre. The temperature sensor is positioned 15mm above the inner cookware bottom - Cookware.

The following standardized cookware sizes and water amount are defined.

Diameter of the cookware bottom [mm]	Diameter of the lid [mm]	Lid hole circle diameter [mm]	Number of holes on the circle [mm]	Total cookware height [mm]	Water Load [g]
150±0,5	165±0,5	110±0,5	11	125±0,5	1030
180±0,5	200±0,5	140±0,5	16	125±0,5	1500
210±0,5	230±0,5	170±0,5	22	125±0,5	2050

Table 7 - Cookware specifications

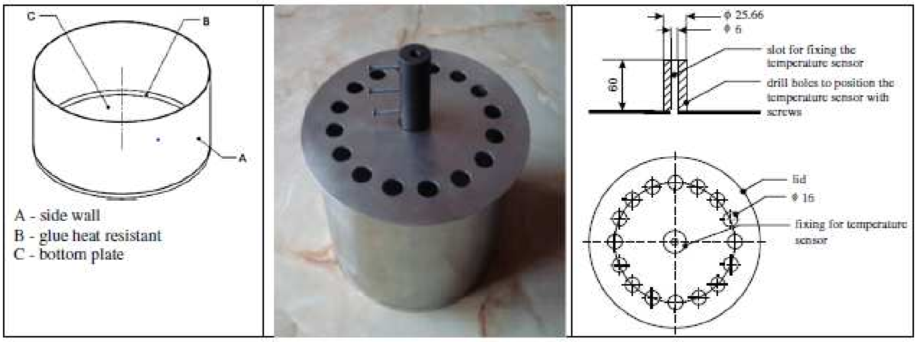


Figure 43 - Cookware

The cooking zone is the zone of the hob which has limitative marks on the surface or attached to it where cookware is placed and heated.

In the case of induction hob, cooking zone on which the pan is heated by means of an induction element below the glass ceramic or similar. The eddy currents are inducted in the bottom of the pan by magnetic field. In this research we have considered circular cooking zone and in particular we define different cooking zone referring to their induction element, the coil.

The following cooking zones and relative coils have been considered (Table 8):

Coil	External dimeter [mm]	Internal diameter [mm]	Numbers of turns [mm]	Litz wire diameter [mm]	Cooking zones diameter [mm]
Coil 1	150	20	22	3	150
Coil 2	180	40	22	3	180
Coil 3	210	60	22	3	210

Table 8 - Cooking zones and coils

The samples under test are commercial induction hobs provided by Electrolux. In this research study, two sample have been considered:

- **Sample 1.** Technical specifications are following (Figure 44):
  - two cooking zones of 180 mm of diameter.
  - Total power 3600 W
  - Power per heater: 1800 W
  - Glass dimensions 300mm x 520mm
  - Product dimensions: 214mm x 470mm
  - Electronic control: touch control.
  - Functional Additional Power.
  - Digital display.
  - Timer
  - Program fine cooking
  - Residual heat indication light
  - System for easy installation

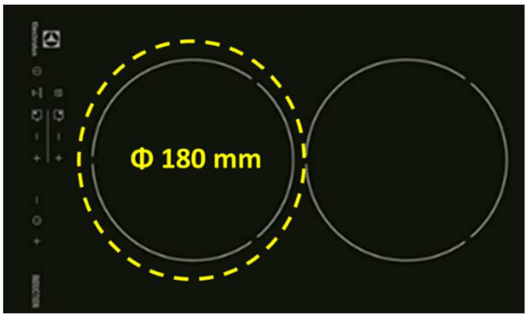


Figure 44 - Sample 1 under test

- **Sample 2**: Technical specifications are following (Figure 45):
    - two cooking zones (one of 150 mm of diameter and one of 210 mm of diameter).
    - Total power 3600 W
    - Power per heater: (induction ϕ210 2000W, induction ϕ145 1600W)
    - Glass dimensions 300mm x 510mm
    - Product dimensions: 214mm x 470mm
    - Electronic control: touch control.
    - Functional Additional Power.
    - Digital display.
    - Timer
    - Program fine cooking
    - Residual heat indication light
    - System for easy installation

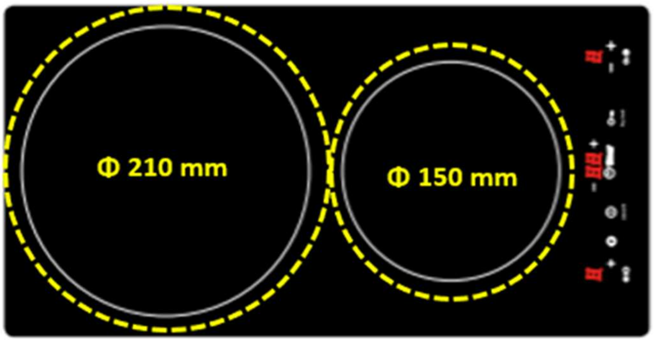


Figure 45 - Sample 2 under test

Test procedures

The experimental tests performed on the device comprises electromagnetic and thermal tests. The electromagnetic tests consist in the measurement of currents and frequency for each power level of the induction hob. These values are used as inputs in the virtual modelling. Standardized pots and coils are employed for the tests. The measurements are obtained with a TEKTRONIK oscilloscope. All the tests are performed considering pot as a load of the system following the different combinations of the Design Test Matrix presented in the following section.

Thermal test: The hob and the pot are placed above a flat bench in a room with a temperature of 23.3°C average. The mass of the pot and of its content was measured by means of a digital weight scale (precision ±1g) at the beginning of the test and at the end of the test. The operation allowed measuring the cumulative mass of water evaporated. A digital data logger (Delta OHM HD 9016, resolution ± 0.1 _C), equipped with a K-type thermocouple calibrated up to 200°C, was used to measure the water temperature. The K-type thermocouple was a fine wire with 0,2 mm diameter and was inserted into the specific hole of the lid of the pot selected for the experiments. Water temperature was thus recorded every 1,3 s using a data logger. Ambient air relative humidity was measured by means of a digital humidity level meter (resolution ± 0.1%). Ambient air temperature was measured by means a digital thermometer (resolution 0.5°C).

A wattmeter was used to read the electric power absorbed by the induction cooker at different power level and an AC/DC Current measurement system was used to read frequency and current on the coil.

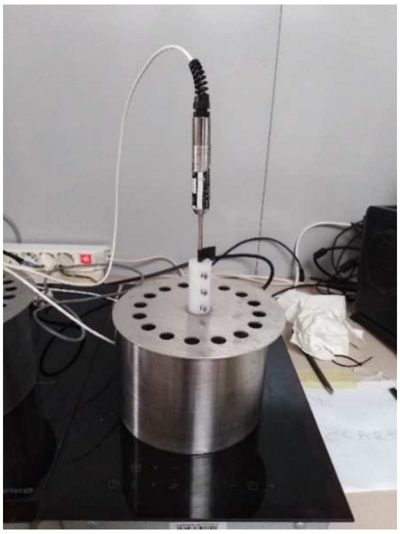


Figure 46 - Test Rig

The experimental campaign consisted in different phases, the first one consisted in a set of water heating procedures in which a given amount of water was heated from a temperature of 15°C to the boiling point, the second one consisted in the reproduction of the energy consumption tests, in which a given amount of water was heated from temperature of 15°C to 90°C and maintained at this temperature for 20 minutes. The first campaign of tests was repeated for different pot geometries, water volumes and power levels of the cooking device in order to know the current and the frequency on the coil at the electrical power level corresponding in order to know the specific level for each phase of the energy consumption test. The “heating up period” is performed at the maximum power level, but when the “simmering period” starts the power have to be reduced a lower power level, so it is necessary to characterize each power level.

The second campaign consisting in the reproduction of the energy consumption test was performed with a set of 3 repetition for each case of the Test Design Matrix presented in the following section.

The 3 repetition were performed by the same person, in the same manner, under the same test conditions in order to have results comparable into low tolerance limits and to highlight repeatability and reproducibility of data and a low degree of uncertainty. All tests were performed in an indoor space, the laboratory of the Department of Energy at Università Politecnica delle Marche. At the end of the test campaign, different results were obtained in order to be compared to virtual ones.

Test Design Matrix

Experiments are in principle comparative tests and they mean a comparison between two or more alternatives. the development of a matrix design is necessary when it is necessary to study several variables simultaneously. Changing is done systematically and the design includes either all possible combinations of the variables. In this case, the variables are the coils and the pot, and the result to analyse is the variation of the performance of the hob depending of them.

The design matrix developed is composed by 9 different combinations, 3 pots and 3 coils. In this research, we evaluated results obtained using standardized coils and standardized pots. For example, standard cookware and coils with the same diameter have different performance than cookware and coils with different diameters.

The table (Table 9) represent the Test Design Matrix developed:

Induction	Cookware	Cookware	Cookware
Coil ϕ150	Pot ϕ150	Pot ϕ180	Pot ϕ210
Coil ϕ180	Pot ϕ150	Pot ϕ180	Pot ϕ210
Coil ϕ210	Pot ϕ150	Pot ϕ180	Pot ϕ210

Table 9 - Test Design Matrix

6.5.7 Analysis and comparison of the results obtained from laboratory and virtual tests.

The following sections shows the results of the virtual model against the experimental data, in terms of temperature water trend and energy, which are the two directly comparable parameters for each case considered.

In the development of the virtual model the parameters that can be set by the user for the simulation include: materials, pot characteristics, ambient conditions, test procedures and specific current and frequency for each power level at which the device is operated (expressed by the heat flux available at the bottom of the pot). The main outputs of the model are the trends of the water heating and the total time to complete the test in order to evaluate the energy consumption.

As explained in the previous section, the virtual model is composed by an electromagnetic simulation and a thermal one. In the electromagnetic simulation the values to insert as input of the system are the current and the frequency, in order to generate the power source for the thermal phenomenon. The electromagnetic solver calculates the magnetic field at the input sinusoidal frequency. A sinusoidal 500 Hz current is assigned to a turn of spiral coil underneath the pot. The coil induces eddy currents and losses in the pot.

Then, the thermal simulation is composed by the two steps corresponding to the "heating up period" and the "simmering period". During the simulation of the "heating up period" when the water reaches the Tc temperature, as described in the regulation *EN 60350-2 - Household electric appliances – Part 2: Hobs – Methods for measuring performance - (IEC 60350-2:2011, modified)*, the input power is reduced in order to keep the water temperature as close as possible to 90°C for the "simmering period", as described by the test.

To simplify the thermal model, the following assumption were considered: natural convection boiling, isobaric process, isothermal surface, transient condition, two phase heat transfer and multiphase in water evaporation. Simulation were considered to solve the transient and incompressible flow, where the air fluid has been considered as a perfect gas. The boundary concerns the total pressure and the ambient temperature reproduce the same required by regulation. The assumption of no-slip condition at the inside wall of the pot is valid and the convection in the pan is a laminar flow. The gravity force of -9.8m/s^2 is added axially in the pot.

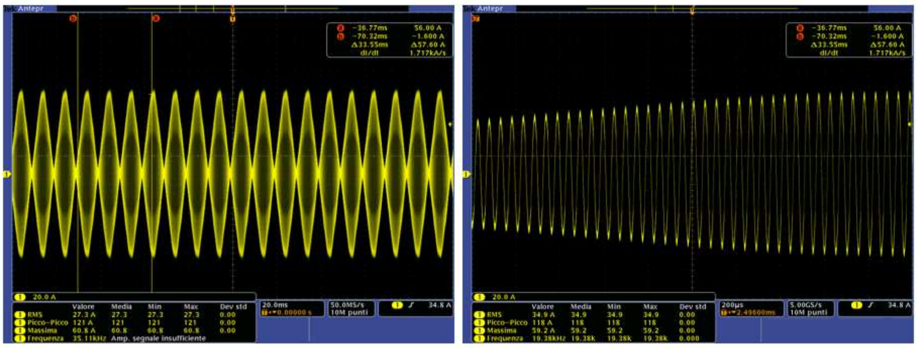
Starting from the values of current and frequency measured experimentally, the energy consumption test was virtually performed for each combination coil-pot presented in the Test Design Matrix. For each combination are presented:

- Diagram of comparison of water trend during the energy consumption test both experimental and virtual;
- The current waveforms measured experimentally for each combination for both the heating up period and simmering;
- The values of rated and simulated power;
- Total time and total energy consumption;

For simplicity, in this work only the combination “Coil Φ180 – Pot Φ150”, “Coil Φ180 – Pot Φ180” “Coil Φ180 – Pot Φ210” will be presented, and a summarizing table will be inserted for the other combinations.

Coil Φ180 – Pot Φ150

Following image (Figure 47) shows the current envelope for the maximum power level and the zoom on waveform during the high frequency generation in order to know the specific frequency for the current value. Maximum power level is the level necessary to the heating up period to heat water from 15°C to 90°C.



	Valore	Media	Min	Max	Dev std
1 RMS	27.3 A	27.3	27.3	27.3	0.00
1 Picco–Picco	121 A	121	121	121	0.00
1 Massima	60.8 A	60.8	60.8	60.8	0.00
1 Frequenza	35.11kHz	Amp. segnale insufficiente			

	Valore	Media	Min	Max	Dev std
1 RMS	34.9 A	34.9	34.9	34.9	0.00
1 Picco–Picco	118 A	118	118	118	0.00
1 Massima	59.2 A	59.2	59.2	59.2	0.00
1 Frequenza	19.38kHz	19.38k	19.38k	19.38k	0.000

Figure 47 - Current envelope at maximum power level and zoom on waveform (coil 180 – pot 150)

When starts “simmering period” it is necessary a reduction of the power of the induction hob in order to maintain water at 90°C. At lower power levels there is a percentage reduction of duty cycle of the induction hob in order to feed coil with lower power than maximum levels. Each power level is characterized by a specific percentage in the reduction of duty cycle. There is a change in the waveform and the system works at different frequency and current. The reduction of the duty cycle is represented by “on-off” period in which the system regulates the current and the frequency to feed to the coil in order to maintain the power corresponding to the level. The different power of each level is characterized by different duration of the “on-off”. In the Figure 48, it is possible to notice a square waveform with “on-off” period.

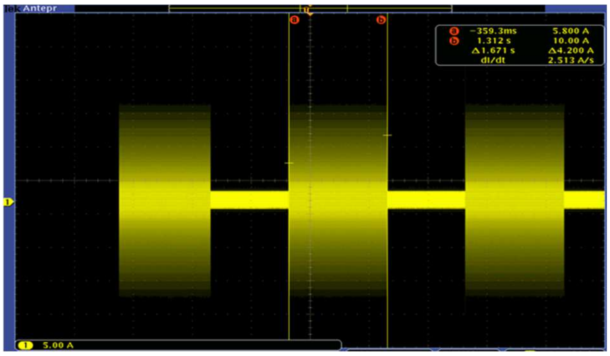


Figure 48 - Square waveform for "on-off period"

	“Heating up” period	**“Simmering” period**
I alimentation [A]	11.24	1.6
I coil [A]	60.8	15.2
Frequency [kHz]	19.38	49
On [ms]	-	1.5
Off [s]	-	1.4

Table 10 – Values of electromagnetic inputs

Table 10 summarize the inputs for the electromagnetic model and the duration of the “on-off period”. Figure 49 shows the results of the energy consumption simulations against the experimental test in terms of water temperature trend over time. Table 11 presents values of power and time of the test periods.

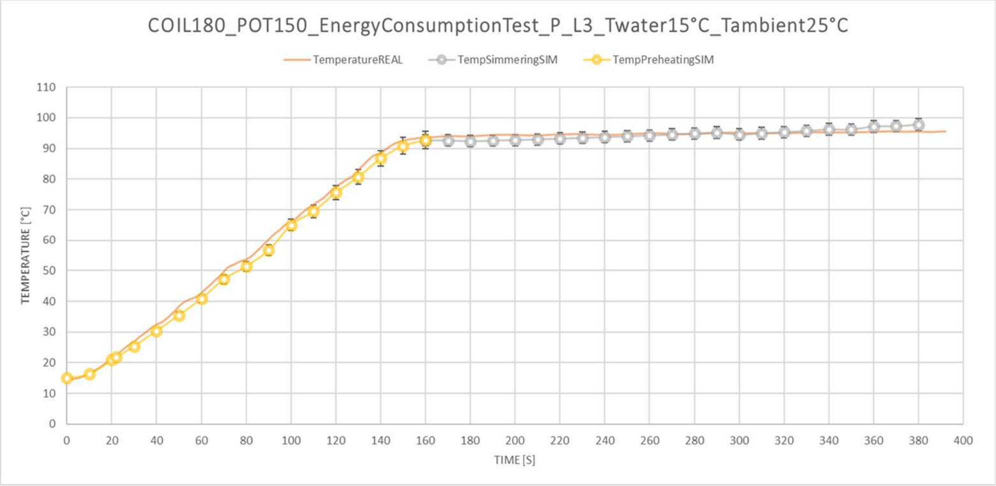


Figure 49 - Energy consumption Test: Virtual and experimental trends (coil 180 – pot 150)

	“Heating up” period	**“Simmering” period**
Rated Power [W]	2585.2	368
Simulated Power [W]	2639.1	360
Time [s]	150	1200

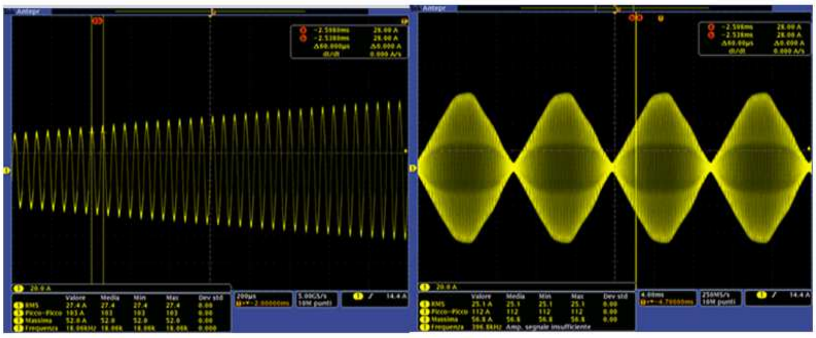
Table 11 - Values of power and time of the test periods

The results are obtained putting as input of the thermal model the power calculated in the electromagnetic model after setting the value of current and frequency. The measurable outputs of the thermal analysis to compare with experimental values are the power and the energy consumption.

The duration of the simmering period both in experimental and simulated case is 1200 s but for simplicity is not reported in the diagram because the temperature water trend of the beginning of the period is the same for whole period.

<u>Coil Φ180 – Pot Φ180</u>

Following image (Figure 50) shows the current envelope for the maximum power level and the zoom on waveform during the high frequency generation in order to know the specific frequency for the current value.



	Valore	Media	Min	Max	Dev std
RMS	27.4 A	27.4	27.4	27.4	0.00
Picco-Picco	103 A	103	103	103	0.00
Massima	52.0 A	52.0	52.0	52.0	0.00
Frequenza	18.06kHz	18.06k	18.06k	18.06k	0.000

	Valore	Media	Min	Max	Dev std
RMS	25.1 A	25.1	25.1	25.1	0.00
Picco-Picco	112 A	112	112	112	0.00
Massima	56.8 A	56.8	56.8	56.8	0.00
Frequenza	396.8kHz	Amp. segnale insufficiente			

Figure 50 - Current envelope at maximum power level and zoom on waveform (Coil 180 – pot 180)

As in the previous combination, at lower level there is a percentage reduction of duty cycle of the induction hob. In this case, the load of the system (the pot) is different from the previous case because of a bigger diameter and the power necessary to "simmering period" is different, consequently the "on-off periods" of the duty cycle differ. Following table (Table 12) reports current and frequency values and the duration of "on-off period".

	"Heating up" period	**"Simmering" period**
I alimentation [A]	10.8	1.7
I coil [A]	56.8	14.6
Frequency [kHz]	18	49
On [ms]		1.6
Off [ms]		1.3

Table 12 - Values of electromagnetic inputs

Figure 51 shows the results of the energy consumption simulations against the experimental test in terms of water temperature trend over time. Table 13 shows values of power and time of the test periods.

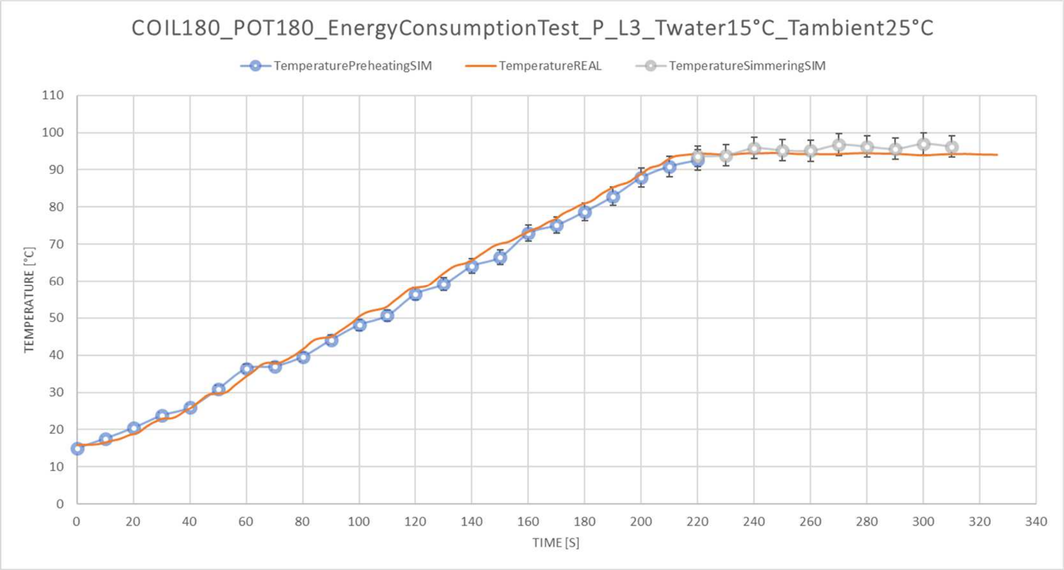


Figure 51 - Energy consumption Test: Virtual and experimental trends (Coil 180 – Pot 180)

	“Heating up” period	**“Simmering” period**
Rated Power [W]	2484	391
Simulated Power [W]	2508	387
Time [s]	220	1200

Table 13 - Values of power and time of the test periods

The results are obtained putting as input of the thermal model the power calculated in the electromagnetic model after setting the value of current and frequency. The measurable outputs of the thermal analysis to compare with experimental values are the power and the energy consumption.

The duration of the simmering period both in experimental and simulated case is 1200 s but for simplicity is not reported in the diagram because the temperature water trend of the beginning of the period is the same for whole period.

Coil Φ180 – Pot Φ210

Following image (Figure 52) shows the current envelope for the maximum power level and the zoom on waveform during the high frequency generation in order to know the specific frequency for the current value.

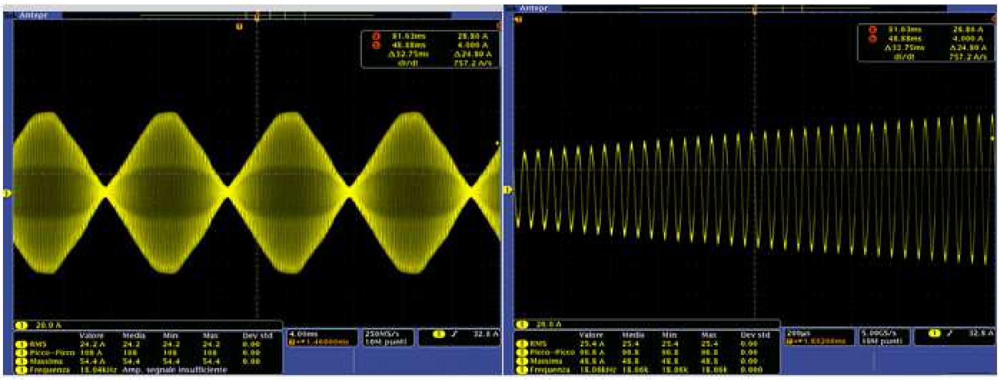


Figure 52 - Current envelope at maximum power level and zoom on waveform (Coil 180 – Pot 210)

As explained in the previous section, for simplicity of discussion, the Table 14 summarize input values and duration of “on-off” period.

	“Heating up” period	**“Simmering” period**
I alimentation [A]	10.5	1.7
I coil [A]	54.4	14.6
Frequency [kHz]	18.6	49
On [s]	-	2.5
Off [ms]	-	541

Table 14 - Values of electromagnetic inputs

Figure 53 shows the results of the energy consumption simulations against the experimental test in terms of water temperature trend over time.

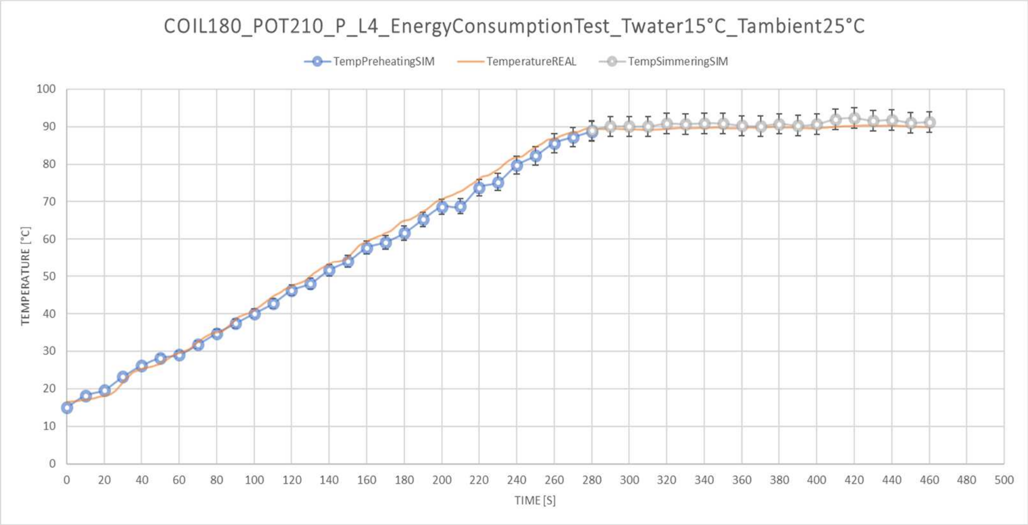


Figure 53 - Energy consumption Test: Virtual and experimental trends (Coil 180 – Pot 210)

The duration of the simmering period both in experimental and simulated case is 1200 s but for simplicity is not reported in the diagram because the temperature water trend of the beginning of the period is the same for whole period.

	“Heating up” period	**“Simmering” period**
Rated Power [W]	2415	391
Simulated Power [W]	2460	380
Time [s]	280	1200

Table 15 - Values of power and time of the test periods

As analysed for the combinations coil – pot with coil Φ180, the same analysis has been carried out for the combination coil-pot with coil Φ150 and coil Φ210. Also, in these combinations, results are different because of the different inputs and geometry of the elements involved, but the discussion and the behaviour of the system are the same. For simplicity, only summarizing tables (Table 16, Table 17) will be shown for the values of "heating up" period and the "simmering" period.

		"Heating up" Period						
	Pot	*I feed [A]*	*I coil [A]*	*Freq [kHz]*	*Rated Power [W]*	*Simulated Power [W]*	*Time [s]*
Coil Φ150	**Φ150**	11,4	61,6	19,59	2508	2490	160
	Φ180	11,3	61,6	19,59	2480	2470	210
	Φ210	11,5	60,8	19,88	2475	2467	300
Coil Φ210	**Φ150**	14,5	76,8	21,48	3335	2490	120
	Φ180	14,5	76,8	21,48	3105	3209	160
	Φ210	11,8	59,2	19,36	2714	2690	230

Table 16 - Summarizing table of "heating up" period

		"Simmering" Period								
	Pot	*I feed [A]*	*I coil [A]*	*Freq [kHz]*	*On [s]/[ms]*	*Off [ms]/[s]*	*Rated Power [W]*	*Simulated Power [W]*	*Time [s]*
Coil Φ150	**Φ150**	1,65	15,4	49	1,5	1,4	363	368	1200
	Φ180	1,58	15	48	1,5	1,4 ms	347,6	338	1200
	Φ210	1,6	15,2	49	2	810 ms	352	338	1200
Coil Φ210	**Φ150**	1,8	20,2	48,8	1,5	1,4	414	398	1200
	Φ180	1,8	20,2	48,8	1,5	1,5	460	439	1200
	Φ210	2	17,6	48,12	1,6	1,4	460	451	1200

Table 17 - Summarizing table of " Simmering" period

In the following figures (Figure 54, Figure 55, Figure 56, Figure 57, Figure 58, Figure 59) the energy consumption test against the experimental test in terms of water temperature trend over time.

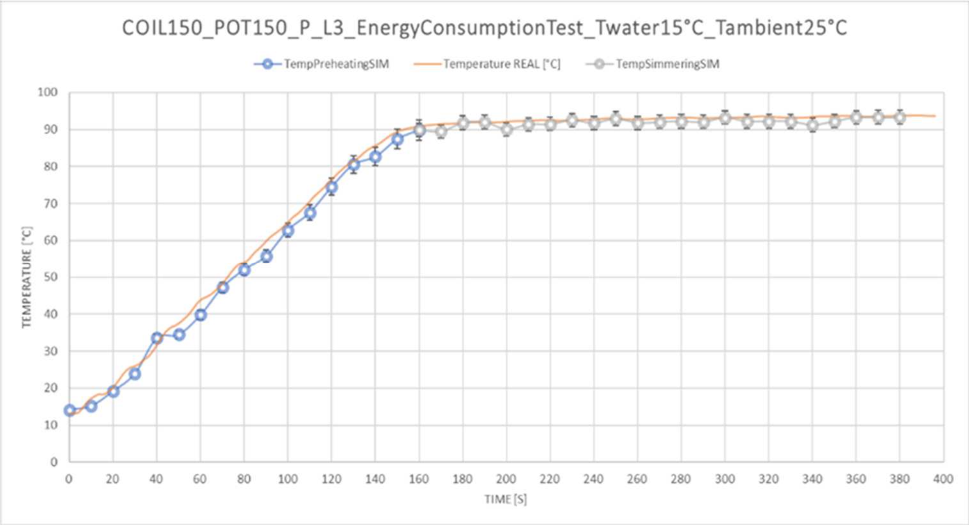


Figure 54 - Energy consumption Test: Virtual and experimental trends (Coil 150 – Pot 150)

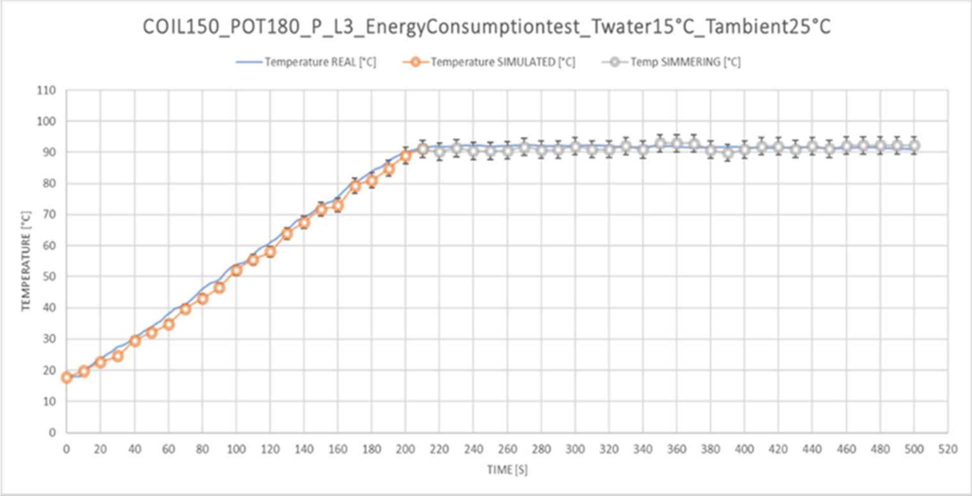


Figure 55 - Energy consumption Test: Virtual and experimental trends (Coil 150 – Pot 180)

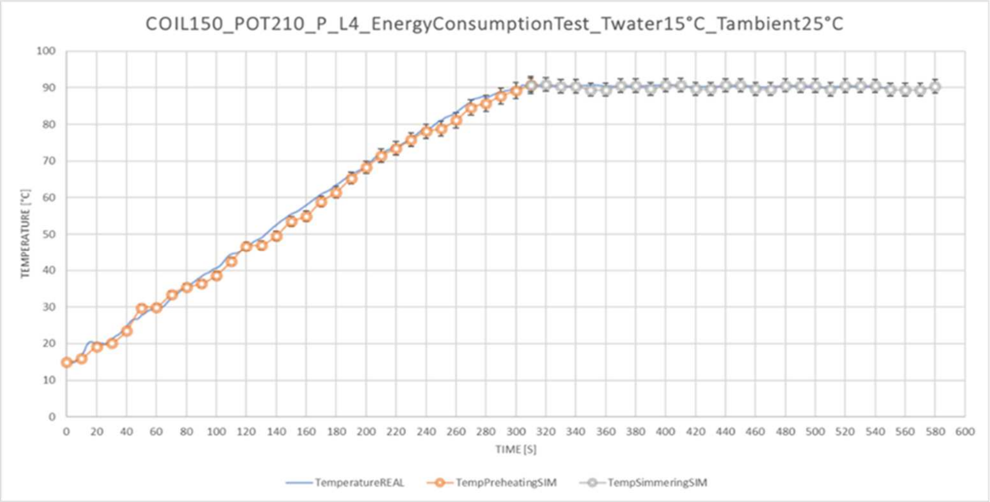


Figure 56 - Energy consumption Test: Virtual and experimental trends (Coil 150 – Pot 210)

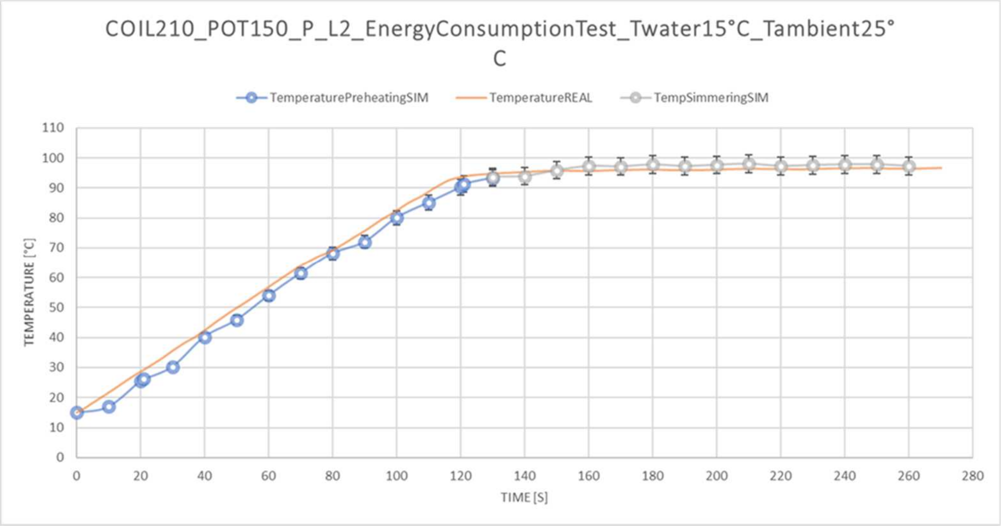


Figure 57 - Energy consumption Test: Virtual and experimental trends (Coil 210 – Pot 150)

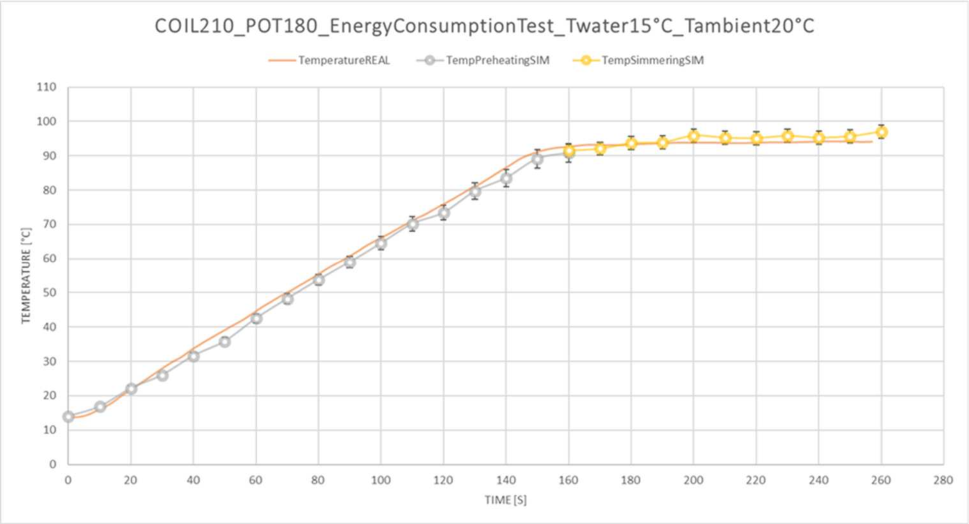


Figure 58 - Energy consumption Test: Virtual and experimental trends (Coil 210 – Pot 180)

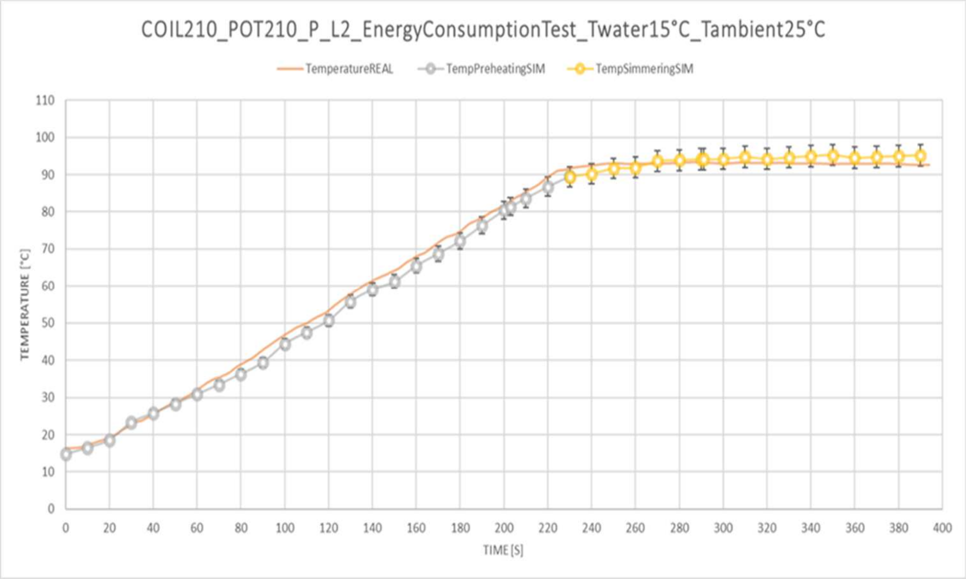


Figure 59 - Energy consumption Test: Virtual and experimental trends (Coil 210 – Pot 210)

6.5.8 Study on virtual models: energy and study of heat transfer

The investigation of heat transfer can be considered as a support to the research work and the virtual analysis collected in database, and represents a methodology of calculation concerning the approaches that are available from a theoretical point of view in heat transfer and heat loss, respectively of the energy balance corresponding to a boiling system according to the testing procedure, under reference to the standard *EN 60350-2 - Household electric appliances – Part 2: Hobs – Methods for measuring performance.*

The calculation is based on analysis of magnitude and direction of heat flow, from where and how the energy/heat comes into system, how it passes through the medium, the transformation that occurs, from where arise the losses and how these could be measured, and generally, the correlating of the parameters that control the boiling system and give us useful information in finding of best solutions which may be applied to increase the energy efficiency of induction hobs.

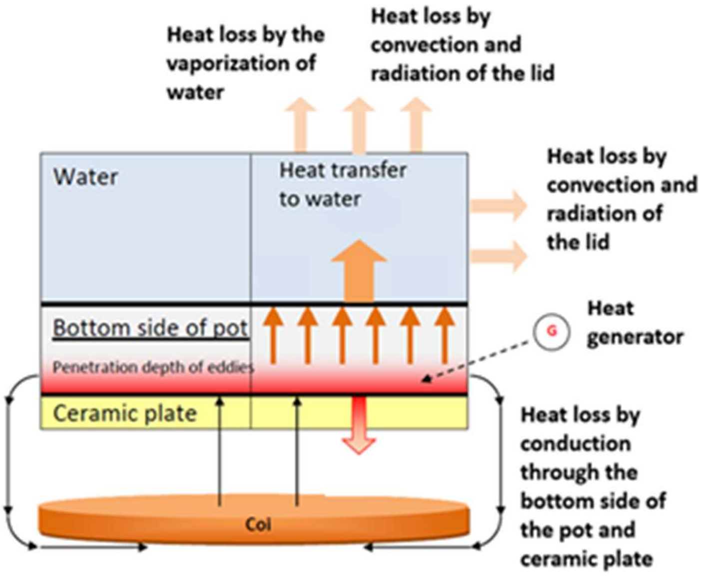


Figure 60 - Heat transfer rates of the system

- Heat loss by convection and radiation from external surfaces of the pot;
- Heat loss by convection and radiation from external surface of the lid;
- Heat transfer by conduction from bottom side of the pot;
- Heat transfer when the water boils during preheating and period (variable temperature from T initial to T final water);
- The calculation of the enthalpy of vaporization water;

Calculation of heat loss by convection from external surfaces of the pot and of the lid;

$$Q_{conv} = h \cdot A \cdot (T_s - T_a) \qquad (W)$$

Q_{conv} = rate of heat transfer, convection (W);

h = the average heat transfer coefficient (W/m^2K)

A = surface of the pot/lid (m^2)

T_s = temperature of the pot/lid at surface (°C)

T_a = temperature of the air sufficient far from the surface of pot/lid, ambient (°C)

Calculation of heat loss by radiation from external surfaces of the pot and of the lid;

$$Q_{rad} = \varepsilon \cdot A \cdot \sigma \cdot [(273 + T_s)^4 - (273 + T_a)^4] \qquad (W)$$

Q_{conv} = rate of heat transfer, radiation (W);

ε = emissivity of material – external surface of the pot/lid

σ = Stephan-Boltzmann coefficient (5.67×10^{-8} W/m^2K^4)

A = surface of the pot/lid (m^2)

T_s = temperature of the pot/lid at surface (°C)

T_a = temperature of the air sufficient far from the surface of pot/lid, ambient (°C)

Calculation of heat loss (rate of heat transfer) in the bottom side of the pot

$$Q_{cond} = k \cdot A \cdot \frac{T_{up} - T_b}{L} \qquad (W)$$

Q_{cond} = heat loss (rate of heat transfer) by conduction through the bottom side of the pot (W);

k = thermal conductivity of the bottom wall of the pot (W/mK);

A = surface that allows the heat transfer by conduction – the bottom wall of the pot (m^2);

T_{up} = temperature above the ceran plate – the contact with the bottom of the pot (C);

T_b = temperature of the internal bottom of the pot (°C);

L = the thickness of the bottom wall of the pot (m);

Calculation of the heat loss by vaporization

$$E_{vap} = m \cdot \Delta H_{vap} \ (J \ or \ Ws)$$

E_{vap} = energy of vaporization of water (J);

m = mass of the water that was vaporized (kg);

ΔH_{vap} = enthalpy of vaporization of water (J/Kg);

The rate of heat transfer (heat loss) by vaporization:

$$Q_{vap} = E_{vap}(Ws) \cdot \frac{1}{n} \left(\frac{1}{s}\right) \ (W)$$

Q_{vap} = rate of heat transfer by vaporization of the water (W);

n = the number of seconds from test;

Calculation of heat rate to heat up water in the heating up period and to maintain the water at constant temperature during the simmering period

$$Q = \frac{m \cdot c_p \cdot \Delta T}{\Delta t} \quad (W)$$

$$Q = \frac{m \cdot c_p \cdot (T_{fin} - T_{in)}}{(t_{fin} - t_{in})} \quad (W)$$

Q = rate of heat transfer to the heat up the water (W);

m = mass of the water to be heated;

T_{in} = temperature initial of the water at the time t_0;

T_{fin} = temperature final of the water at the time t_{fin};

t_{in} = instant initial;

t_{fin} = instant final;

The calculation procedure of the energy transfer and the energy balance

Calculation of the energy transfer

The rate of energy transfer that comes in system, by heat, work and mass is equal to the net energy transfer that leaves the system by heat, work and mass, because there are not changes with respect to the internal energy.

$$E_{IN} - E_{OUT} = \frac{\delta E_{system}}{\delta t} \quad (J \; or \; Ws)$$

E_{IN} = energy that comes in system (J, or Ws);

E_{OUT} = energy that leaves in system (J, or Ws);

$\delta E_{system}/\delta t$= rate of change in internal kinetic or potential energy (J, or Ws) = 0;

In other words, the energy is a property of the system (water boils in a pot at constant temperature) and the value of that property does not change (or the energy accumulated by water that was needed to reach a specific temperature, remains constant), unless the state of the system changes (by increasing or decreasing of the water temperature).

In heat transfer analysis, we are usually interested only in the forms of energy that can be transferred as a result of a temperature difference, that is, heat or thermal energy.

In such cases it is convenient to write a heat balance and to treat the conversion of electrical energy into thermal energy as heat generation.

Therefore, the meaning of the energy that comes into the boiling process (E_{IN}) is represented by the heat generated by the heat flux through the bottom side of the pot that makes water to boil,

$$E_{IN} = E_{generation} = q_n \cdot A = Q \ (J or\ Ws)$$

and the energy that leaves out the boiling process (E_{OUT}) is represented by the total heat loss,

$$E_{OUT} = Q_{total\ loss} \ \ (J or\ Ws)$$

$Q_{total\ loss}$ = total heat loss (J,or Ws);

The energy balances

The total energy delivered to the system is the sum of the energy spent during the preheating period and the energy spent during Simmering;

Total Energy delivered to system = Energy spent during Preheating + Energy spent during Simmering

$$E_{IN} = E_P + E_S \quad (Wh)$$

E_{IN} = value input of the virtual model (Wh);

Energy balance during Preheating Period

The electric energy from the power supply will turn into another form of energy, like the heat that will flow to/from the system as follows:

- Into electric/electronic means belonging to the induction hob, with loses due to the available technology methods.
- Heating up the bottom wall of the pot with loses by conduction effect.
- Heating of the ceran plate, with loses by conduction effect;
- Heating up the water (by charging of thermal capacity of the liquid from a low to a predefined temperature, complying to the standard requirements);
- Escape of the heat through the external walls of the pot and lid, by convection and radiation;
- Water evaporation/vaporization;

Firstly, the maximum heat loss can be considered when heating up the system, in fact the pot and the water, or by charging with heat of a large capacity, or thermal mass.

Secondly, a large heat capacity of the bottom wall of the pot and the thermal mass of the ceran plate will need an appreciable amount of heat to reach equilibrium close to 90^{o}C.

Generally, the heating up period occurs in a short time, therefore some losses by convection and radiation are minimized because the system temperature is increasing progressively during the test and the differences between the thermal and system and the temperature of the environment may be considered at an average value.

The amount of the heat loss by evaporation/vaporization has a low value because of the short testing time.

Energy spent in system:

- Q p cond – loss by conduction
- Q p conv – loss by convection
- Q p rad – loss by radiation
- Q p evap – loss by evaporation

Energy gain by system:

- E_{pw} - Energy accumulated by water

$$|E_P| = |E_{PW}| + |Q_{Pcond}| + |Q_{Pconv}| + |Q_{Prad}| + |Q_{Pevap}| \qquad (Wh)$$

The energy spent during the preheating period corresponds mainly to the energy needed to rise up the water temperature, including losses.

Energy balance during Simmering Period

The electric energy from the power supply will turn into another form of energy, like the heat that will flow to/from the system as follows:

- Into electric/electronic means belonging to the induction hob, with losses due to the available technology methods;
- Keeping the water under boiling conditions, or keeping the bottom wall of the pot hot enough in order to maintain the water temperature above 90°C, with losses by conduction effect;
- Keeping up the ceran plate at a predefined temperature almost equal to the bottom wall temperature of the pot during the whole simmering period, with losses by conduction effect;
- Heat losses through the external walls of the pot and lid, by convection and radiation;
- Water evaporation;

Taking account about the aforementioned information, the heat from the bottom wall of the pot is requested to keep up water temperature (under simmering conditions, so the water temperature to be above 90°C), and to cover all losses from system.

The most consistent heat loss from the system can be considered when the water is going to boil, in fact the heat loss by vaporization especially when the nucleating boiling occurs. Anyhow, the nucleate boiling occurs locally, at the interference between liquid and solid, or at the bottom wall of the pot, but in some cases due to low vapor pressure, the energy remains in system and is not totally discharged into environment. The simmering period occurs in a long time (1200 seconds) and the losses by convection and radiation have higher values because the system has reached the highest temperature which is kept during the entire testing period.

Energy spent in system:

- Q s cond – loss by conduction
- Q s conv – loss by convection
- Q s rad – loss by radiation
- Q s evap – loss by evaporation

Energy gain by system:

- E_0 – energy overshoot from preheating that will be discharged in water during the simmering period

$$|E_S| = |E_0| + |Q_{Scond}| + |Q_{Sconv}| + |Q_{Srad}| + |Q_{Sevap}| \qquad (Wh)$$

The energy spent during the simmering period corresponds only to the energy needed to maintain the boiling process, including losses.

The analysis of the heat transfer that occurs during the energy consumption test of the induction hob can be carried out through the virtual model. In fact, during the process of product development, simulations can be used to evaluate the performance of the virtual models, thus reducing time and costs. The virtual test should reproduce the behaviour of the product and consequently, it is possible to analyse the heat transfer rates. This study follows the Test Design Matrix developed for the Virtual Models. In the following figures (Figure 61, Figure 62) an example of heat transfer phenomenon of the product during the energy consumption test.

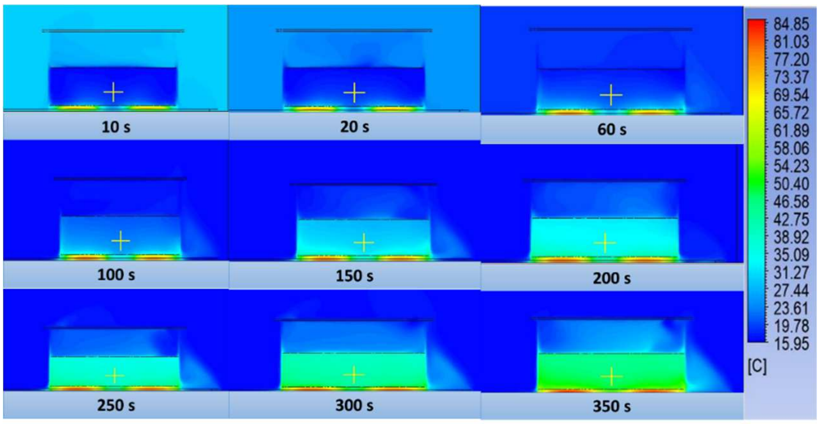


Figure 61 - Heat transfer of the system during the test

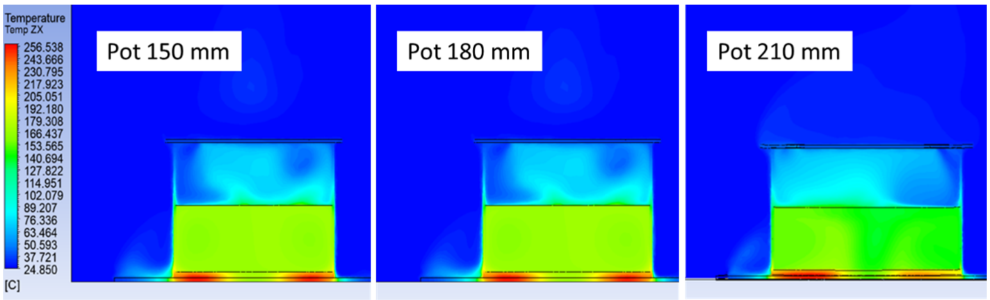


Figure 62 - Trend temperature for different type of pot at the end of preheating phase

Coil Φ180 – Pot Φ180

Calculation of the heat transfer rate (energy balance) during the **preheating period** (220s). In terms of power:

Heat transfer rate	In terms of power [W]	In terms of energy [Wh]
Q heat up water	2042,624383	119,153089
Q convection POT	8,118399933	0,473573329
Q radiation POT	1,054524149	0,061513909
Q convection LID	0,143141517	0,008349922
Q radiation LID	0,023078342	0,001346237
Q ceranplate	230,4893115	13,44520984
Q conduction bottom	103,8603651	6,058521295
Q vaporization	114,2285091	6,663329698
TOTAL	2500,541712	145,8649332

Table 18 – Heat transfer rates of the system – Preheating Period

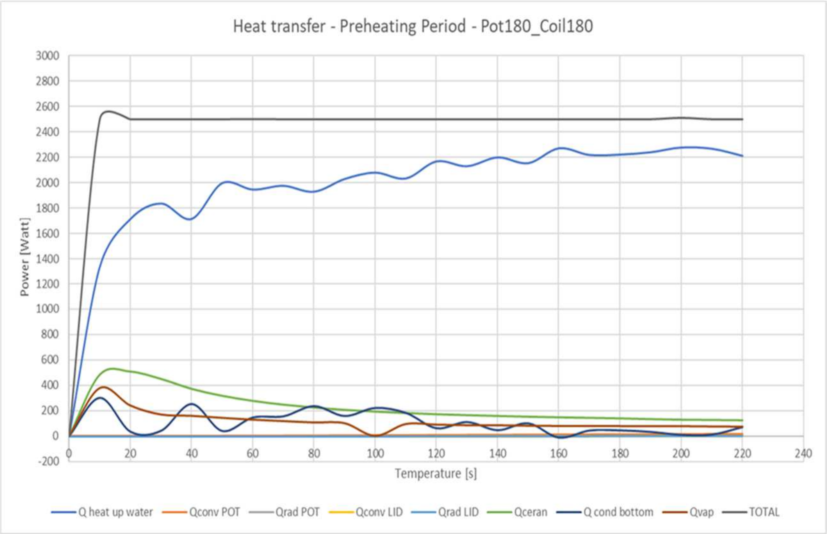


Figure 63 - Power rates of the system

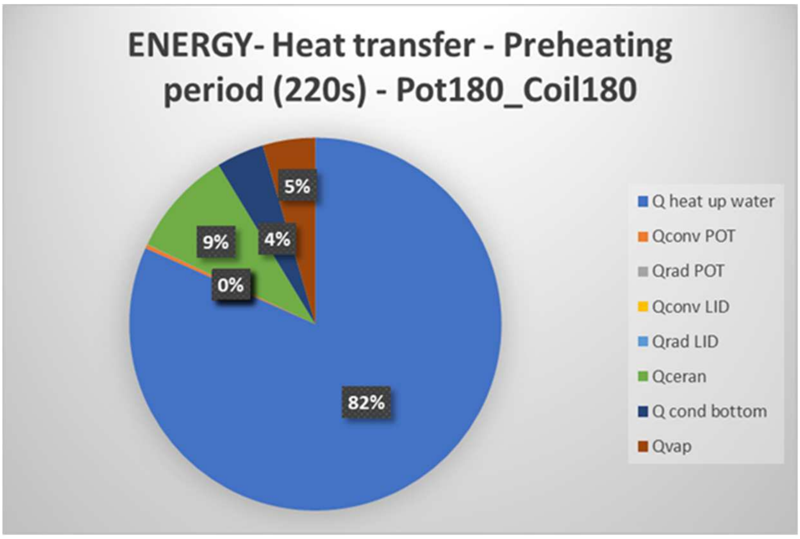


Figure 64 - Balance of heat transfer

Calculation of the heat transfer rate (energy balance) during the **simmering period** (1200s). The most important transfer rate is due to the keeping of water near 90°C and the losses for convection and radiation have high value because of the high temperature reached by the pot.

In this analysis for simplicity, there is the calculation of the transfer rate needed to keep water and the other contribution are considered losses.

Heat transfer rate	**In terms of power [W]**	**In terms of energy [Wh]**
Q heat up water	96,5	32,16
Losses	290,5	96,83
TOTAL	387	129

Table 19 - Heat transfer rates of the system – Simmering Period

The energy balance diagram – performance test complied to EN 60350-2 is presented is the following (Figure 65):

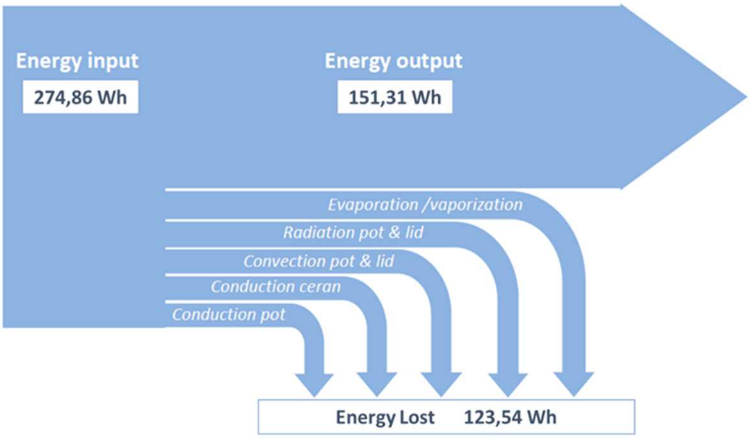


Figure 65 - Energy Balance Diagram - Performance Test (Coil 180 – Pot 180)

Coil Φ180 – Pot Φ150

Calculation of the heat transfer rate (energy balance) during the **preheating period** (160s). In terms of power:

Heat transfer rate	**In terms of power [W]**	**In terms of energy [Wh]**
Q heat up water	1853,79722	82,39098757
Q convection POT	6,568025311	0,291912236
Q radiation POT	0,853745487	0,037944244
Q convection LID	0,056052827	0,002491237
Q radiation LID	0,010245661	0,000455363
Q ceranplate	266,6214142	11,84984063
Q conduction bottom	376,7121115	16,74276051
Q vaporization	135,3811847	6,01694154
TOTAL	2640	117,3333333

Table 20 - Heat transfer rates of the system – Preheating Period

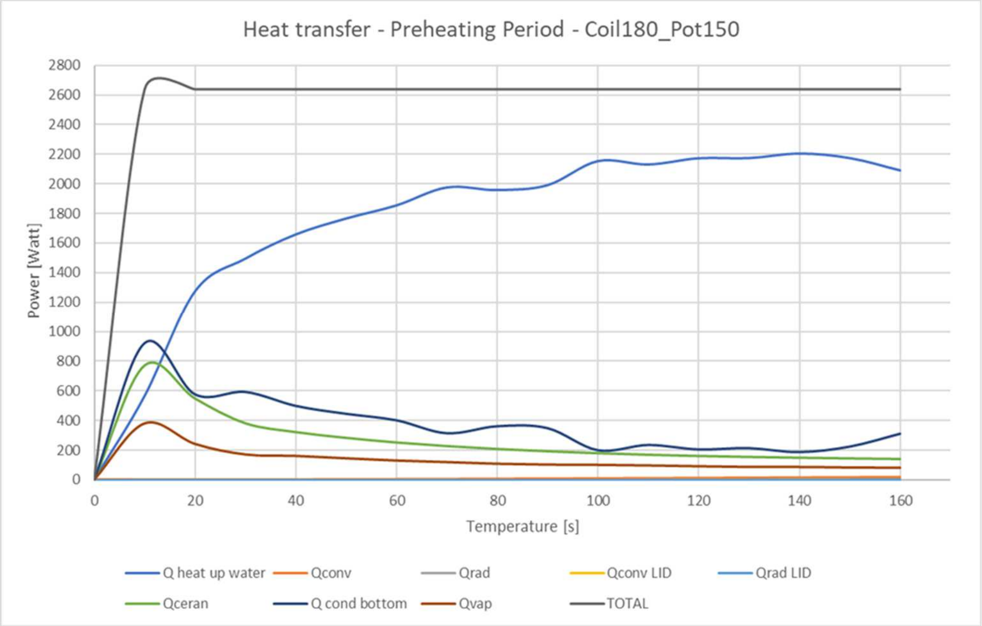


Figure 66 - Power rates of the system

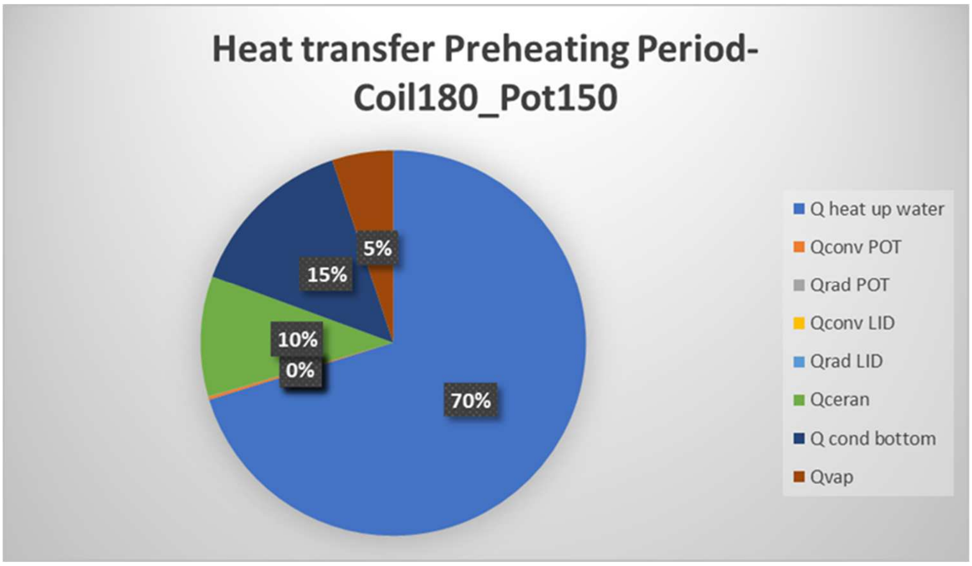


Figure 67 - Balance of heat transfer

Calculation of the heat transfer rate (energy balance) during the **simmering period** (1200s).

Heat transfer rate	**In terms of power [W]**	**In terms of energy [Wh]**
Q heat up water	129,96	43,32
Losses	250,04	83,3
TOTAL	380	126,6

Table 21 - Heat transfer rates of the system – Simmering Period

The energy balance diagram – performance test complied to EN 60350-2 is following (Figure 68):

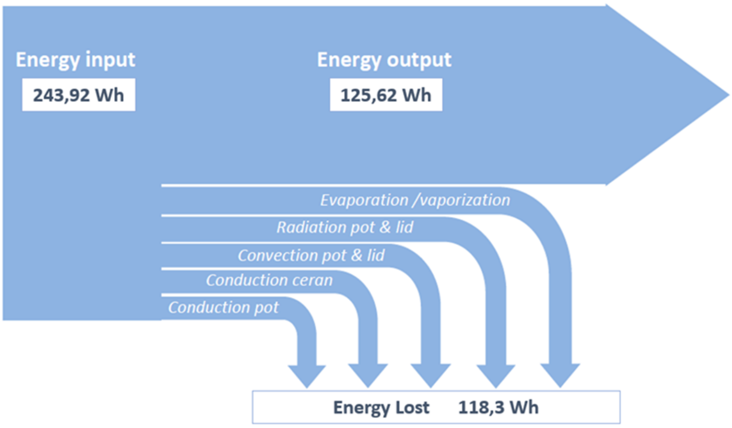


Figure 68 - Energy Balance Diagram – Performance Test (Coil 180 – Pot 150)

Coil Φ180 – Pot Φ210

Calculation of the heat transfer rate (energy balance) during the **preheating period** (300s). In terms of power:

Heat transfer rate	**In terms of power [W]**	**In terms of energy [Wh]**
Q heat up water	2101,892399	175,1576999
Q convection POT	9,480772377	0,790064365
Q radiation POT	1,226098902	0,102174908
Q convection LID	0,763355324	0,063612944
Q radiation LID	0,101409699	0,008450808
Q ceranplate	184,1778281	15,34815234
Q conduction bottom	56,01427554	4,667856295
Q vaporization	105,9273414	8,827278447
TOTAL	2353,656139	196,1380116

Table 22 - Heat transfer rates of the system – Preheating Period

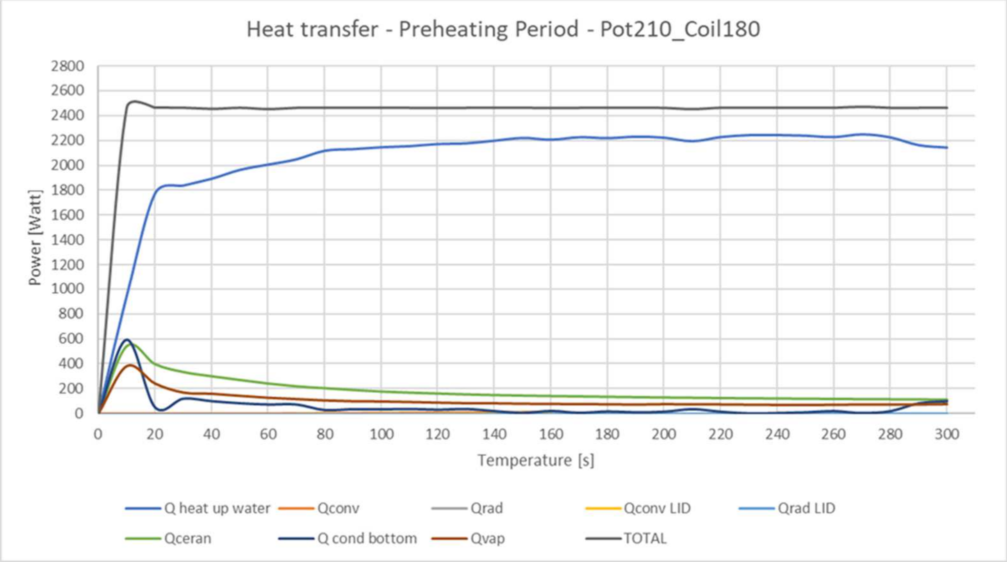


Figure 69 - Power rates of the system

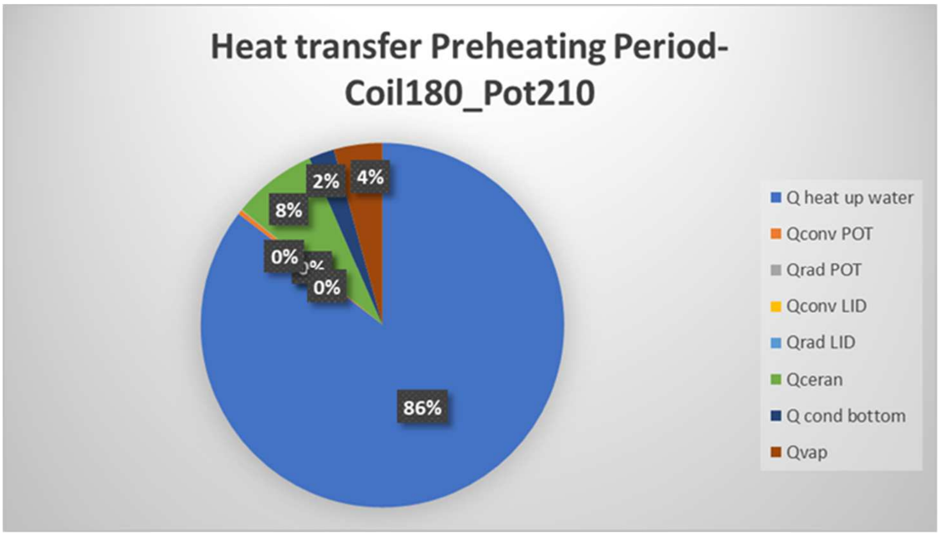


Figure 70 - Balance of heat transfer

Calculation of the heat transfer rate (energy balance) during the **simmering period** (1200s).

Heat transfer rate	In terms of power [W]	In terms of energy [Wh]
Q heat up water	144,09	48,03
Losses	223,91	74,63
TOTAL	368	129

Table 23 - Heat transfer rates of the system – Simmering Period

The energy balance diagram – performance test complied to EN 60350-2 (Figure 71):

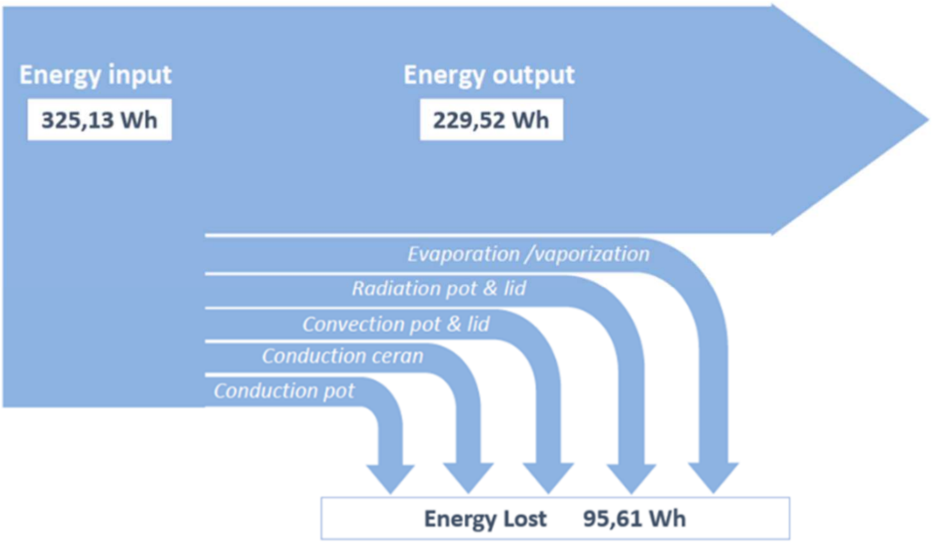


Figure 71 - Energy Balance Diagram – Performance Test (Coil 210 – Pot 210)

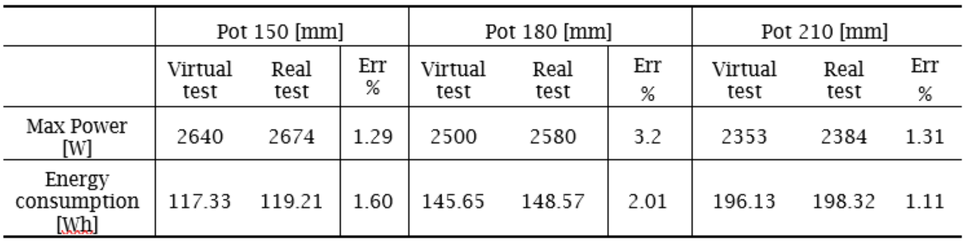
For simplicity, only summarizing table will be shown the energy input and output rates for the performance test complied to EN 60350-2 of other combinations of the Test Design Matrix (Table 24).

	Energy Input [Wh]	Energy Output [Wh]	Energy Lost [Wh]
Coil Φ150 – Pot Φ150	237,29	113,9	123,39
Coil Φ150 – Pot Φ180	256,76	162,92	93,84
Coil Φ150 – Pot Φ210	316,87	180,45	136,42
Coil Φ210 – Pot Φ150	258,16	168,28	89,88
Coil Φ210 – Pot Φ180	292,92	191,94	100,98
Coil Φ210 – Pot Φ210	336,79	307,67	29,12

Table 24 - Summarizing table for the performance test

6.5.9 Discussion

The main objective of this research is to evaluate the performance of an induction hob during the conceptual and embodiment design in terms of energy efficiency to classify the product using the European Standard. The proposed methodology can be extended to different types of appliances that must be compliant to eco-design directives. Household appliances are typical EuP (energy-using product) and ErP (energy related product), and thus the energy consumption during the use phase is very important. In this context, using the proposed approach, the designer can evaluate the product consumption and efficiency. The innovation of the approach lies in the definition of a knowledge management system that can support the designer in rapid evaluation of the energy efficiency of products. Using the proposed approach, the engineer becomes more aware of the product efficiency and can compare different configuration cases during the early design phase. The knowledge stored in the V.E. database can be also used to support the decision-making phase before starting a new design project to reduce time and costs from the beginning. The aim of this approach and of the virtual analysis repository is to fill the gap between industrial needs and eco-design requirements and demonstrate how knowledge-based system can propose an approach that surpasses other state-of-art solutions. In particular, the approach is innovative in the context of household appliances. Using the proposed approach, the designer is more aware of the relation between the product configuration and the energy consumption in operation. These days, the delivery of products that are complaint with higher energy efficiency indexes is very important. In fact, customers are increasingly aware and conscious of product energy efficiency and consumption. The results of the virtual models show a good overall accuracy of the model, especially as regards the temperature trend over time. A good correspondence, both in terms of the maximum power values and the energy consumed during the test is noticed (max error = 3% for the 180 [mm] pot), as presented in the following table (Table 25):



	Pot 150 [mm]			Pot 180 [mm]			Pot 210 [mm]		
	Virtual test	Real test	Err %	Virtual test	Real test	Err %	Virtual test	Real test	Err %
Max Power [W]	2640	2674	1.29	2500	2580	3.2	2353	2384	1.31
Energy consumption [Wh]	117.33	119.21	1.60	145.65	148.57	2.01	196.13	198.32	1.11

Table 25 - Comparison between virtual and real test for coil 180 mm and different type of pot

A slightly lower accuracy, as expected, is obtained in the simmering period because of the difficult to keep constant the temperature of the water due to the precision of the model employed to compute the evaporation phenomenon.

Furthermore, the average error between the simulation and the measurement is low, as it is observed, the simulated water temperature trend is very similar to the measured ones, which confirms the validity of the proposed model. Possible improvements can be the development of a DOE (Design of Experiments) with more parameters to consider and to configure new product. While these virtual models were analysed by simulations and collected in the database using a DOE approach based on CFD analysis, other configurations can be studied and optimized to maximize the efficiency. The number of variations and parameters used in this case study were defined to show how the proposed method works and the study of other variation can lead to a further improvement of the product.

Chapter 7.

Conclusions: perspectives and limits

Conclusions

The present research thesis investigates the main issue of eco-design when it is applied to the product design inside industrial companies and proposes a structured framework to support designers since the early phase of design process in the development of sustainable products.

The aim of the V.E. Approach is to support engineers in ecological design choices during the early phase of product design, by collecting and making available guidelines and eco-knowledge in a structured database that integrates information related to eco-design and virtual prototyping.

The novelty in this approach is the association of virtual prototyping to environmental aspects during the product design process and the possibility to share knowledge using a database among designers which are not involved into the environmental issue.

The V.E. methodology has been defined starting from the analysis of most recently literature in the field of eco-design methods and tools. From this analysis emerged that despite a great number of existing tools and methods, the developed solutions are too far from the industrial needs and companies face some difficult to implement eco-design in their design process.

The state-of-art highlights the different challenges of eco-design implementation, from basic eco-design principles to the need for eco-design tools and ways to manage data and information during the design process. Four main problematics are emerged from this analysis concerning:

- The integration of the environmental aspects into the product design process;

- The creation and the collection of a specific eco-knowledge to share and increase inside the company and to use as support for designers;
- The difficult to analyse the performances and use phase of products, in particular the energy related ones, in compliance with eco-design standard;
- The lack of valid support to designers into the decision-making process to evaluate environmental issues to choose the most satisfying alternatives possible.

The research work developed the proposal on these gaps and tries to transform these ones in point of strength of it. The four research objectives which lead the study were identified as follow:

I. *The first objective of this proposed work is to create a comprehensive framework combining existing design tools (e.g. CAD, VP) and environmental requirements and able to support the designer choices throughout the industrial product development.*

II. *The second objective is the development of a structured repository for the collection, classification and efficient sharing of eco-knowledge able to store all the useful information for the development of sustainable products.*

III. *The third objective is the creation of a virtual model (specific for each product) able to simulate energy and environmental performances in compliance with eco-design and energy labelling standards.*

IV. *The fourth objective is the creation of an eco-design tool which can guide the designers in the eco-sustainable choices in the first phase of product design process.*

Each of these research objectives has been transformed into “functions” which the approach satisfies, and which represent the detailed contributes given to the problematics previously highlighted. To satisfy these functions, the V.E. approach develops a database. In fact, similarly to the mathematical language, the functions are laws which links the domain and the codomain. The domain is represented by the database in which a set of variables such as guidelines, environmental analysis, virtual prototyping studies etc. are stored. The codomain is represented by all possible "outputs" for each member of codomain, which are the possible design solutions which satisfy functions. The contribute of the research work is the formalization of the needs for a good integration of eco-design in the design process and the satisfaction of them. The detailed contributions and their linked actions carried out in this research work are following:

I. **Integration:** The creation of a comprehensive framework combining existing design tools and environmental requirements able to support the designer's choices throughout the product development;
II. **Eco-knowledge creation:** The development of a structured depository for the collection, classification and efficient sharing of eco-knowledge able to store the information for the support in the development of sustainable products;
III. **Analysis of performances:** The creation of virtual models able to simulate the energy and environmental performances of products in compliance with eco-design standards;
IV. **Support decision-making:** The creation of an eco-design tool with specific guidelines which can guide designers in the eco-sustainable choices since the early phase of product design.

The developed approach links eco-design guidelines, company eco-knowledge, virtual prototyping studies and product characteristics and allows to take account environmental considerations since the first design phases. In this way, designers, even if low skills on environmental sustainability, can be supported in applying strategies for the development of ecological products.

The V.E. database was at first developed as a prototype in order to validate it through an experimentation in companies. This experimentation was divided into two phases, which allowed to understand directly the difficulties related to the practical and effective use of eco-design tools inside an industrial company and to confirm and validate the conclusions derived from the analysis of the literature in this topic. The V.E. approach allows to overcome these lacks thanks to the collection in its database of eco-design guidelines, company eco-knowledge, virtual prototyping studies and environmental analysis. Their organisation in a structured database, their link with specific parameters of the product, facilitate their retrieval and support the design phases without adding complexity. The case study chosen for the experimental studies is the induction hob, a household appliance subjected to the European eco-design regulation (Directive 209/125/EC).

The first phase of experimentation was aimed at validating the methodology in the identification of the environmental hot spots in the development of sustainable products through the use of environmentally ranked guidelines stored in the database and the relative tool. This phase was conducted in an industrial company whose name will be protected for reason of industrial privacy. This experimentation was conducted evaluating the applicability, the usability/effectiveness of guidelines in their application during the design process and at the end in the customization of the database through the input of specific company guidelines. The results of this experimental phase recognize the guidelines tool as a useful design tool for a company to increase the awareness of designers in environmental choices during the design process. This last statement was confirmed by the good results in terms of applicability and usability/effectiveness obtained by the tool during its implementation in the company. The implementation of the tool has allowed to understand the database strength points, its limit and its potentialities, and has provided very interesting starting points for future improvement of it. The tool appeared very adaptable to company's need, nevertheless, some modification is needed to facilitate the customization.

The second phase of experimentation took place in Electrolux s.p.a company with the aim to validate the support of virtual prototyping during the early design phase. In this phase virtual models of the product were modelled in order to simulate the performances and the use phase and to investigate the influence of different parameters on them. In particular, in this research work the virtual models reproduce the energy consumption test required by the directive European Standard EN 60350-2:2013. A test design Matrix was developed in order to study different configuration of the system and for each one a thermal study was conducted. The thermal study allowed to evaluate the overall energy consumption and the specific energy rates of system, which otherwise would be difficult to study through physical test. The results show a good overall accuracy of the model, especially in the reproduction of the energy consumption test. Furthermore, designers have evaluated the possibility to consult virtual prototyping studies a good support to be integrated into the traditional design phase, able to provide an important previous energy evaluation of the product and to facilitate the implementation of eco-design strategies.

These results, obtained by two experimental phases, confirm the interest of industrial companies for the proposed approach and the need for future investigation and development of the V.E. approach. The activities conducted during the experimental phase confirm the and validate the conclusion derived from the analysis of the literature. Designers usually not have knowledge on environmental topics and therefore they need a guide to acquire practice on eco-design through the product development process.

During this research period of three years the V.E. database has been developed in a prototypal way for a specific case study but opens large possibility to be applied to different products. It is very adaptable thanks to the use of virtual prototyping as a concrete instrument of eco-design and opens to the possibility to implement new functionalities. In fact, it would be interesting to test and validate the methodology and the tool in industrial situation different from the household appliances design in order to identify the potential lacks or weakness. The V.E. database could be used for eco-design of strongly innovative products in order to test the viability of the solution.

Other possible improvements move on the possibility to make the database more “active”, for example with the adding of modules for instantaneous environmental and performances analysis.

In conclusion, it is possible to state that the PhD years have allowed to develop a methodology and a tool that can represent a good and reliable means to support designers in the implementation of eco-design strategies during the design process.

Perspectives and limits

The V.E. approach developed in this research work is applicable to the industrial context and the results of the experimental phases have shown that it could fit in a global agenda of the companies. The experimental phases have highlighted that the system of activities suggested by the approach may be applied to different business contexts.

- The results of the first experimentation provided the company with “proactive” solutions to integrate environment into product design process. The direct contribution of the tool has conducted the company to reflect on the improvement of the environmental sensibility of the design departments. The tool supports designers and engineers, encouraging them to improve the sustainability performances of products providing them with a structured and iterative process that allows them to identify and define tasks and address violation to sustainability dimensions. The tool was used successfully in the feasibility, concept and simultaneous engineering phases. In order to provide additional validation of the tool, the designers participating in the assessment sessions were also asked if they identified any sustainability aspect of their product that was missing. Feedback received led to improvement and refinement of the tool. During the case study was noticed that the guidance of guidelines was crucial to maximize the positive outcomes of the using of the tool. And at the same time the first guidance of an expert could give a quick and general introduction into the concept of sustainability in the context of product development and explain the purpose and the methodology of the tool. On one hand, the fact that an expert should be present for the first implementation can be considered to be a disadvantage of the tool. On the other hand, the presence of an expert can also be interpreted as an advantage, since it fosters dialog and knowledge sharing between the expert and the designers.

- The results of the second experimental phase demonstrate a great support to the designer of the virtual models and of the reproduction of the energy consumption test, but at the same time open wide perspective to the use of virtual prototyping in the context of eco-design. The use of virtual prototyping in the presented approach can lead designer to strategic decision since the early design stage and it is configured as a sort of bridge between the concept and the detailed design stage. The virtual models represent a systematic approach with both qualitative and quantitative analysis which enables decision makers to examine strength and weakness of product from a performance point of view. The approach gives the possibility to build techniques to integrate measurable performance properties to environmental requested performance, identifying critical factors as material selection and available information about materials. The limit of the application of V.P as a tool towards the eco-design is the importance to accurately transform customer needs into actual sustainable forms and functions of the products. Further, it is essential for the designers involved in the development process to visualise the design as effortlessly as possible and to gai a comprehensive understanding of the functional behaviour of the product. The major contribution of this research is that by the use of virtual prototyping as an eco-design tool, it allows more projects stakeholders, not just engineers and designers, to get involved in the decision-making process of a new product. Generally, the phases of the development of a product are linked together through information, material, energy, etc., in this case also the environmental dimension adds to the last ones. The integration between the environmental and technical requirements is achieved through the consideration of a co-relation of them in quantitative models. This works bridges an important gap between engineering design and environmental experts, as it incorporates the definition and the integration of environmental and functional requirements to design parameters. As future perspective of the approach is to think to the optimization of the virtual models collected in the database. Optimisation has been a focus of the design research for many years and has mostly focused on evaluation of design parameters of the product. Such research has assumed that objective functions can be expressed algebraically and that it is possible to differentiate the functions that assist algorithms that try to perform gradient descent. However, future efforts can be focused to the optimization of the product. In fact, the objective of optimisation can be summarised simply as to maximize or minimise objective functions across a set of parameters, realising that environmental aspect is a considerable challenge.

The focus of sustainable product development is directed toward identifying opportunities, recognizing mutual benefits and facilitating the exchange of knowledge between different actors of the product development such as environmental experts and designers. An approach based on the integration of eco-design and sharing of knowledge is favourable because this methodology enables companies to initiate and monitor a product development process in a structured way in situations that are characterized by a lack of information and high degree of uncertainty. The proposed approach presents non-negligible benefit in an environmental point of view, because thanks to the dynamic solutions of information exchanges, the effort required to collect up-to-date data based on the progress of the design will be considerably reduced. In addition, the designer can compare quickly different design elements involved in the analysis results without having to restart the complete modelling of the system.

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Appendix A. Environmental Guidelines

In following

Table 26, all the 162 eco-design guidelines retrieved from literature and ranked by the Eco-design Score (E.S.) are shown. For confidentiality reasons, the company guidelines (stored during the implementation of the tools in companies), which are stored into the tool in the same structure and the evaluation through the Applicability Score by companies, can't be shown.

ID	Guideline	E. S.
1	Create the forms with good material, structure and durability, minimizing wear and deformation.	**9**
2	Aim for rigidity through construction techniques such as reinforcement ribs rather than 'over dimensioning' the product.	**9**
3	Aim to express quality through good design rather than over dimensioning the product.	**8**
4	Aim at reducing the amount of space required for transport and storage by decreasing the product's size and total volume.	**8**
5	Consider transporting the product in loose components that can be nested, leaving the final assembly up to a third party or even the end user.	**7**
6	Design the product to minimize the use of auxiliary materials	**7**
7	Find alternative for exhaustible materials	**8**
8	Avoid energy intensive materials such as aluminium in products with a short lifetime.	**9**
9	Select just one type of material for the product as a whole and for the various sub-assemblies.	**9**
10	Where possible, select mutually compatible materials.	**8**
11	Make use of parts and materials supplied by local producers.	**7**

12	Preferably use materials that do not require additional surface treatment.	**7**
13	Minimize material use in the product and package and utilize one kind of material not compound one.	**7**
14	Use minimum volumes and weights of packaging.	**7**
15	Use the lowest energy consuming components available on the market.	**9**
16	Make use of a default power-down mode.	**8**
17	Ensure that clocks, stand-by functions and similar devices can be switched off by the user.	**6**
18	If energy is used to move the product, make the product as light as possible.	**7**
19	If energy is used for heating substances, make sure the relevant component is well insulated.	**8**
20	Choose the last harmful source of energy.	**9**
21	Reduce consumption of energy and resources during distribution, production and use.	**8**
22	Encourage the use of clean energy.	**8**
23	Study the feasibility of reusing consumables	**8**
24	Design the product to use the cleanest available consumables.	**8**
25	Make the default state that which is the most desirable from an environmental point of view	**8**
26	Encourage the production department and suppliers to make their production processes more energy efficient.	**8**
27	Apply visual elements and information encouraging environmental consciousness of the product.	**8**
28	Design the product in modules so that the product can be upgraded by adding new modules or functions later.	**10**
29	Design the product in modules so that technically or aesthetically outdated module can be renewed. For example, make furniture with replaceable covers which can be removed, cleaned and eventually renewed.	**10**

30	The product should have a hierarchical and modular design structure; the modules can then each be detached and remanufactured in the most suitable way.	**10**
31	Design to make co-using parts among the functions or equipments and minimize additional input.	**8**
32	Design the product's appearance so that it does not quickly become uninteresting, thus ensuring that the product's aesthetic life is not shorter than its technical life.	**8**
33	Ensure that maintaining and repairing the product becomes a pleasure rather than a duty.	**8**
34	Give the product an added value in terms of design and functionality so that the user will be reluctant to replace it.	**9**
35	Design the product with the possibilities of local service and maintenance companies in mind.	**8**
36	Design the product in accordance to the socio-economic needs and possibilities of the user's groups.	**7**
37	Asses the opportunities to design products for low-income groups.	**7**
38	Design to provide users with cues for assembly and disassembly of the product for easy upgrading and repair.	**8**
39	Give the product a classic design that makes it aesthetically pleasing and attractive to a second user.	**8**
40	Combine constituent functions in one component so that fewer production processes are required.	**7**
41	Design to ensure easy accessibility of the product for inspection, cleaning, repair and replacement of subassemblies or parts.	**9**
42	Design to pursue the form with minimum artificial element or useless decorations.	**6**
43	Design to allow the product to be used as the 2nd and the 3rd usage by integrating various objectives and functions.	**9**
44	Do not use materials or additives which are prohibited due to their toxicity.	**8**
45	Avoid materials and additives that deplete the ozone layer such as chlorine, fluorine, bromine, methyl bromine, halons, foams, refrigerants and solvents that contains CFCs.	**8**

46	Find alternatives for surface treatment techniques such as hot-dip galvanization, electrolytic zinc plating and electrolytic chromium plating	**6**
47	Find alternatives for non-ferrous metals such as copper, zinc, brass, chromium and nickel because of the harmful emissions that occur during their production.	**7**
48	Select production techniques which generate low emissions, such as bending instead of welding, joining instead of soldering.	**6**
49	Choose production technologies that require fewer harmful substances and generate fewer toxic emissions.	**6**
50	Toxic materials should to be concentrated in adjacent areas so that they can easily be detached.	**9**
51	Use recycled materials wherever possible to increase the market demand for recycled materials.	**8**
52	Use secondary metals such as secondary aluminium and copper instead of their virgin (primary) equivalent.	**7**
53	Use recicled plastics for the inner parts of products which have only a supportive function and do not require a high mechanical, hygienic and tolerance quality.	**8**
54	Make use of the unique features (such as variations in colour and texture) of recycled materials in the design process.	**8**
55	Avoid materials which are difficult to separate such as compound materials, laminates, fillers, fire retardants and fiberglass reinforcements.	**8**
56	Preferably use recyclable materials for which a market already exists.	**8**
57	Avoid the use of polluting elements such as stickers which interfere with recycling.	**8**
58	Stimulates arrangements for recycling of materials by local companies which can substitute (part of) the raw materials of the company.	**8**
59	Recycle production residues within the company.	**7**
60	Use production techniques that generate less wastes and organize efficient in-company re-use and recycle systems for the remaining waste.	**8**

61	Allow components and parts to be recycled and reused in the other products.	**7**
62	Coil elements must be well insulated to avoid losses	**8**
63	Reduce the gap between the coil surface and the bottom of the pot to ensure the operational phase	**8**
64	Use commercial/regular diameter for the coil in order to simplify the product to increase accessibility in case of disassembly, repair or replacement of subassemblies or parts	**9**
65	Use material with a high conductivity for the coil to avoid energy consumption	**8**
66	Make sure that the ohmic loss distribution is homogeneous to preserve efficiency of product	**8**
67	Use product with a good electrical efficiency	**8**
68	Use parts with a satisfactory lifetime	**8**
69	Have favourable parameters for efficient energy supply, such as high impedance and power factor	**8**
70	Have low sensitivity to changes in the part dimensions and positioning in specified range to simplify disassembly, repair or replacement of subassemblies parts	**9**
71	Have reasonable cost compatible with the lifecycle of the product	**9**
72	Provide a good arrangement of the part in the assembly of product to avoid additional material	**7**
73	Provide a cooling system air through the electronics beneath the cover to preserve them from breakages and avoid energy consumption	**8**
74	Provide a cooling system air through the electronics beneath the surface of the glass to preserve them from breakages and avoid energy consumption	**9**
75	Use elements which generates the less level noise.	**7**
76	Avoid internal cooling fan which generates noise.	**6**
77	Avoid elements which can generate electromagnetic noise.	**7**

78	Use elements with a high fluid dynamics efficiency	**7**
79	Use glass ceramic tops with a high resistance to avoid breakage and preserve the lifecycle of the product	**8**
80	Specify correct position of the pan on the glass ceramic top to avoid energy consumption	**8**
81	Provide a control system to shut down the element if a pot is not present or not large enough	**7**
82	Provide a glass ceramic flat and smooth to simplify the cleaning and to minimize the use of toxic product	**8**
83	Provide a monitoring system for delivered power	**5**
84	Provide a monitoring system to keep a pot just simmering, or automatically turn an element off when cookware is removed	**6**
85	Use coil wire which decrease the skin depth and increase magnetic permeability to have good performance of product	**6**
86	Use coil wire that increase the current near the surface of the metal and increase the electrical resistance	**6**
87	Use litz wire for the coil to increase performances of product	**6**
88	Use coil wire in order to reduce skin effect and consequent heat generation in the coil and increase efficiency of product	**6**
89	Avoid heat generation in the coil to not affect the efficiency of product	**6**
90	Provide a thermostat to measure the temperature of the pan to avoid energy consumption	**6**
91	Provide a thermostat to maintain a target temperature to not affect the efficiency of product	**6**
92	Design as a standalone surface unit to increase accessibility in case of disassembly, repair or replacements of subassemblies and parts.	**6**
93	Insert a memory setting, one per element, to control the time that the heat is applied to avoid energy consumption	**6**

94	Insert in the product a "zone less" induction cooking surface with multiple induction coils in order to use different energy sources	**6**
95	Make the product less expensive as possible compatibly with the market	**6**
96	Use materials with good thermomechanical properties to have a good lifetime of product	**6**
97	Use a glass ceramic with good thermomechanical properties to have a good lifetime of the product	**6**
98	Use glass ceramic which can sustain repeated and quick temperature changes to preserve the product lifecycle	**6**
99	Use a glass ceramic with low heat conduction coefficient to increase efficiency of product	**6**
100	Minimize electronics leaks.	**4**
101	Apply visual elements to indicate operative state of product	**5**
102	Insert a system to avoid power outage	**6**
103	Insert an automatic switch off system if the pan is removed in order to save energy	**6**
104	Insert different heat settings and programmes for precision cooking and energy saving	**6**
105	Select high quality materials because can provide high performance ad low weight, reducing the overall volume of material needed.	**9**
106	select material characterized by high resistance, because the selection of materials characterized by high resistance can determine a product longer life time, thus reducing the overall environmental impacts.	**8**
107	Use materials with an established close loop for which it is possible to realize one the following End of life Scenario: reuse, remanufacturing, recycle.	**7**
108	Avoid toxic substances: If the use of toxic substances cannot be avoided, a high detail in the BOM description is necessary for those substances. In this way an easily identification and separation could be guaranteed at their EoL.	**7**

109	Minimize material variety and select the same material for different parts where possible: materials used in different product components should be uniformed, especially for components that are connected each other. In this way, their separation can be avoided, thus minimizing the disassembly operations and making easier recyclability operations.	**7**
110	Avoid the use of alloy's and composite materials: Alloy and composite materials have a low recyclability degree. Composites are mixtures of materials which have been chosen to achieve a particular set of properties – examples being glass reinforced plastics (GRPs), Carbon composites, and MDF. They are (generally) more expensive than standard materials, require specific production techniques and are generally difficult to recycle. However, given their structural properties, they should not be replaced with sub-standard materials for high-performance or safety-critical applications.	**8**
111	Prefer to use materials that come from recycled processes, instead of use virgin ones. Select materials with a high percentage of recycled inputs.	**7**
112	Select materials with a high level of recyclability: The use of recycled materials prevents non-biodegradable waste ending up in landfills. They also require less energy in terms of processing, and provided there is no contamination from other materials, can last several cycles before becoming obsolete. Reducing the number of additives used in materials can help reduce contamination and retain material properties.	**7**
113	Reduce the use of packaging and facilitate the identification of the packaging materials: Packaging materials should be reduced in weight and in volume, using the same case for different components if possible. A codification of packaging materials should be defined for the identification of EoL treatments.	**7**

114	Minimize material inputs: Simplification through the reduction of parts and general form will not only reduce waste and provide for easier EoL treatment but will also reduce both assembly and disassembly costs. It is important that the simplification of the design does not compromise its function or structural integrity. It is also important not to compromise the aesthetic qualities of the product, given how this may affect the product’s perceived value and subsequent revenue.	**8**
115	Prefer the use of the same materials in different product components, especially for those that are connected together, to increase their level of recyclability.	**8**
116	Try to reduce the component number in order to reduce the whole product weight and consequently its environmental impact.	**8**
117	Optimize product functionality: a critical review of the structural design with a view to the functions needed may result in a considerable simplification by integration of functions. Combining several functions in one component does not only reduce material input but also facilitates assembly and disassembly as there are fewer connecting parts.	**8**
118	Assure that all components can be easily reached to be disassembled. Components that present high level of damage or wear should be collocated in strategic and easily accessible positions.	**8**
119	Ensure easy access to product component in particular a rapid access should be guaranteed for critical component that need specific EoL treatments.	**6**
120	Identify components that are likely to wear or break and ensure easy access to these components: Components with the highest percentage of wear od damage should be identified and marked in the BoM with specific code. Assure that all components that have more frequent need of external actions are easily accessible. In this way the product can be repaired and its life time increase.	**6**
121	Opt for surface treatments or structural arrangements to protect products from dirty, corrosion, and wear	**8**

122	Consider greenhouse gas emissions, volatile organic compounds, and acidification phenomena	**5**
123	Consider the aquatic emission of heavy metals and organic pollutions	**6**
124	Consider the leaching of pollutants into the ground	**6**
125	Consider the secondary use of primary process waste: In order to minimize the environmental impact related to the use of the product, the minimization of waste production con contribute to the reduction of product environmental load.	**6**
126	Reduce number of production phases: In order to minimize the environmental impact related to the use of the product, the minimization of production process con contribute to the reduction of product environmental load.	**6**
127	Opt for packaging solutions that minimize the weight, while determining a safety protection for the product.	**7**
128	Choose local suppliers where possible and select those that allow to minimize the distance from the production site	**6**
129	Optimize transport planning, by preferring the transportation means that minimize environmental impact	**7**
130	Analyse the energy related component inside your product and evaluate alternatives able to reduce the energy consumption along the life cycle.	**6**
131	Include in the product all those strategies that allow to optimize its functionality, increasing the life time and reducing the damage possibility	**7**
132	Maximize useful life of the product	**8**
133	Describe hazardous substances used in the product in BOM in order to easily identify and separate them to permit specific EoL treatments	**8**
134	Identify and mark material used in order to easily identify the EoL treatments for the component. Specific material identification code should be used.	**6**
135	Realize a correct selection of fasteners in order to facilitate the product manual disassembly, to reduce its time and	**6**

	cost and to facilitate the material separation, designers should follow some rules during the product design.	
136	Select connection types that can be disassembled with the use of simple tools. This facilitate the disassembly operations and reduce the relative time, thus improving the product disassembly performances.	**6**
137	Collocate connection elements to make them rapid and simple to separate and to access in assembly and disassembly.	**7**
138	Use connection elements of similar dimension in order to minimize the number of tools needed for disassembly	**6**
139	Identify if contaminations among components occur or not. Estimations should be based on the know-how of manufacturers and designers	**6**
140	Identify and reduce surface covers (like paints, varnishes) and bonding agents (glues and adhesives) because of their potential to contaminate materials to be recycled.	**6**
141	Mark materials, especially plastics, above a minimum mass. Several standards have been also introduced to regulate nomenclature and labelling of plastics, rubbers and polymers	**6**
142	Investigate the need of adhesives and investigate their effect on component recyclability. The use of adhesive should be reduced in order to avoid recyclability problems.	**6**
143	if adhesives are necessary, use adhesive with low hazardous solvent emission	**6**
144	if adhesives are necessary, minimize use of silicone	**6**
145	if adhesives are necessary, choose seals which can be easily removed	**6**
146	if adhesives are necessary, remember clean surfaces facilitate recycling	**6**
147	Evaluate the economic saving along all the lifecycle of high efficiency motors	**6**
148	Ensure that the packaging is designed for and is robust enough for re-use. Ensure that facilities for cleaning, repair or reconditioning are available if this is necessary before the packaging can be re-used	**6**

149	Encourage the packaging recyclability: Try to avoid materials, combinations of materials or designs of packaging that might create problems in collecting, sorting or recycling.	**6**
150	Encourage the packaging separation.	**6**
151	Minimise the use of substances or materials that might create technical, environmental or health problems in the recycling process or in the disposal of recycling residues.	**6**
152	Design plastic packaging for recycling involves particular challenges. Try to use materials of different densities so as to facilitate separation. Un-Pigmented polymers are more valuable as recycled than pigmented, so if you are using a colourless plastic packaging material it is better to attach an adhesive label than print on the packaging itself. The polymer identification symbol should be shown clearly.	**6**
153	Evaluate the purchasing cost of high efficiency motors	**6**
154	When using electrical circuits: mount components on a printed circuit board with detachable leads, do not solder.	**6**
155	when using electrical circuits: use plugs that push into place and can easily be pulled out	**6**
156	Ensure reversibility of assembly procedure which is a prerequisite for easy disassembly in case of manufacturing defects and for repair work during use stage, and, in particular, for disassembly after end of life.	**6**
157	Design product structure for easy disassembly (uniform directionality for assembly and disassembly work). Uniform directionality for assembly and disassembly will also provide for ease of sorting structural components and optimize assembly work.	**6**
158	Minimize time and paths for disassembly, it is imperative to minimize work input for this stage. Thus, minimizing time for disassembly is a prerequisite for the recyclability of parts and components. In most cases, this will also reduce assembly time for the product. Therefore, paths for (dis)assembly should be minimized, connections should be easily detachable, etc.	**6**

159	Use easily detachable connections (also after end of life!) in order to reduce time consuming disassembly work. In addition, non-destructive disassembly is a prerequisite for the recycling or reuse of structural parts. If parts are damaged during disassembly only the material can be recycled; however, on account of the destruction of the material's structure this alternative yields less value than direct reuse of parts	**6**
160	Preferably use renewable raw materials for packaging	**6**
161	Preferably use recycled materials or packaging materials suitable for established recycling processes	**6**
162	Label packaging materials (incl. instructions for disposal)	**6**

Table 26 - Environmental guideline

Appendix B. Questionnaire of Evaluation

In the following

Table 27, all the questions, divided for topics of the questionnaire for the usability/effectiveness of the tool.

	USABILITY
1	***Compatibility***
a	When you open the tool, it is clear what steps you can/should perform.
b	When you open the tool, it is easy to understand how to activate a specific tool function.
c	The tool icons are easily associated with the functions they perform.
d	It is easy to enter all the required information through the interface.
e	The tool is aesthetically pleasing to the user.
2	***Consistency and standards***
a	The filter functions return relevant guidelines to the user.
b	There are no errors in the tool filtering function.
c	In general, the software functions are consistent during each analysis step.
3	***Explicitness***
a	The steps the user has to perform to begin the analysis are clear and easy to identify.
4	***Flexibility and Control***
a	The structure of the tool is flexible, allowing the user to perform the analysis steps according to his/her needs.
b	The user is able to perform the analysis which he/she considers best for his/her needs.

5	***Functionality***
a	The tool outputs (the guidelines) are useful for the user
b	The retrieved guidelines are easy to translate into design choices.
c	The software satisfies user expectations from a functional point of view.
d	The software is able to meet your needs.
6	***Informative Feedback***
a	The tool clearly details the analysis carried out to create the output.
7	***Language and Content***
a	The tool functions are easy to understand and are written in a simple and direct language.
b	The tools outputs (guidelines) are easy to be understood and are written in a simple and direct language.
c	The tool table contents are written in a clear way.
d	Displaying the guidelines within a table is useful to improve their readability and comprehension.
e	The language used throughout the tool is easily understandable for the user.
8	***Navigation***
a	The tool structure allows the user to rapidly perform the required analysis.
b	The filtering toolboxes are quickly and easily identifiable within the interface.
c	The tool evaluation/calculation icons are quickly and easily identifiable inside the interface.
d	The main interface icons are easy to find and accessible.
e	Overall, navigation within the tool allows the user to easily and quickly access all functions.
9	***User Guidance and Support***

a	The software contains guidance material which supports and helps the user to understand how it works.
b	The user guidance is easy for the user to understand.
c	The user guidance is written in a simple and direct language.
d	The user guidance is able to fully support the user during initial usage of the tool.
10	***Visual Clarity Description***
a	All the information displayed on the interface is clear.
b	All the information displayed on the interface is well organised.
c	All the information displayed on the interface is unambiguous and easy to read.
	EFFECTIVENESS OF THE TOOL
1	***Impact on the traditional design process***
a	The impact of the tool use in terms of time dedicated to the analysis is admissible and compatible with the traditional time of the design process.
b	The impact of the tool, in terms of competence to acquire, is admissible and compatible with the actual company employees competency or are necessary specific skills.
c	The modification of the traditional design process to use the tool is admissible for your company and easy to realize.
2	***Personnel to involve if the tool will be implemented inside the company***
a	The personnel inside the company is able to use the tool and to interpret its results (after appropriate training activities).
b	The introduction of the tool inside the company doesn't need the involvement of new personnel with specific background on eco-design issues.
c	The personnel inside the company is able to use the tools and to easily understand its suggestions.

d	The training sessions organized for the tool are adequate and sufficient to be able to use correctly the tool.
e	The timing requested for the training sessions is adequate in relation to the company traditional time dedicated to training activities.
f	It is not necessary to use specific staff with eco-design background to conduct the training activities.
g	The introduction of the tool can determine new relationships among the different company roles involved inside the company.
	USER INTERACTION WITH THE TOOL
1	user suggestions how to improve the tool:
2	user impression about customization (applicability/input of company guidelines) of the tool:
3	user suggestion about customization:
4	user suggestion about graphics:

Table 27 - Questionnaire of usability/effectiveness evaluation