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Extended summary

# Toward Eco-design: an integrated lifecycle engineering system to develop sustainable mechatronic products and services

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**Abstract**. The design process in the past was focused mainly on cost-reduction, increasing product quality, product quantity and time-to-market reduction. For these reasons several design tools have been developed to assist designer in this activity.

Nowadays, the environmental aspects have become widely considered and represent an important and success market factor, in fact, the consumers are developing an increasing environmental sensibility so they are attracted by “green products”. From this consideration derive the need for design tools to support the designers in considering both the environmental and the cost aspects into the design process.

In recent years several tools have been developed at this scope. IT systems, for example, are currently employed in the design process and they can be grouped under the PLM (Product Lifecycle Management) system family. PLM can be viewed as the integration of several tools as mentioned before, with methods, people and processes throughout all stages of a product’s life. On the other hand there are tools for specialist to assess and calculate the environmental impact of products by different methods. LCA (Life Cycle Assessment) is the most common and recognized method to determine the environmental burden of products and services.

The research goals could be synthesized as the definition of a new eco-design approach and tools for the environmental and lifecycle cost consideration in the design process. This research work is a step toward the development of integrating eco-design platform by linking IT systems (PLM and CAD software) and lifecycle methodologies (LCA and LCC). The proposed eco-design environment represents the way to develop sustainable products and services in early phases of product design. In order to verify the advantages of using the approach and the platform, several functional groups of mechatronic products and household appliance prototypes have been manufactured to experimentally measure the results of the choices made with the eco-design platform.

The target foreseen for these kind of products is a strongly reduction in global energy use compared to the current situation and a reduction in industrial waste. Furthermore, additional advantages in terms of product assemblability, logistic management of suppliers and lifecycle cost reduction have been noted.

**Keywords.** Eco-design, lifecycle engineering, design tool, IT integrated platform, end-of-life.

# 1 Problem statement and objectives

In the last decades, most studies have shown an increasing worldwide need for products and services which are qualified in terms of sustainability. Sustainability means creating an economic system that provides for quality of life while renewing the environment and its resources. The three pillars of sustainable development are: economic, environmental and social. In particular, a growing environmental awareness has arisen among consumers, leading them to a perceived generalized positive attitude on product green label [1]. This is a consequence of environmental policies and laws which are moving in the eco-sustainability direction [2], [3], [4], [5]. Industrial firms and companies tend to produce products compliant with these directives and provide the market with more sustainable products [6]. Energy and environmental policies are significant factors behind the trends in industrial companies in Europe and all over the word [7].

The main issue of this new business scenario is the impact on the Small and Medium Enterprises (SMEs). SMEs often follow a pragmatic approach on environmental design and solutions rather than a systematic one. Thus, they focus on one or several aspects, found to be important "by accident", driven mostly by technical requirements, instead of applying a thorough hot spots analysis or an eco-design tools. For these reasons, the new eco-design techniques find several obstacles to penetrate in the engineering departments [8].

One of the means of achieving sustainable development in this new business scenario is to design ecological products and services. Eco-designing products indeed encourages a global approach designed to prevent or minimize impacts emerging throughout the whole lifecycle of products and concerning all types of environmental impacts [9]. Eco-design is an umbrella phrase for a wide variety of environmentally based activities, from incremental production process adaptations, to wholesale design innovations [10].

Several eco-design approaches and tools have been proposed and developed in recent years. Generally, these solutions are either too qualitative or too detailed in terms of needed input data and, mainly, they are not well integrated into the design process workflow. Actually, they represent just the rough beginning of a new eco-design era. The current eco-design tools vary in data presentation and design process implementation [11].

The eco-design tools can generally be classified into three categories: tools based on checklists, tools based on Life Cycle Assessment (LCA), and tools based on Quality Function Deployment (QFD) [12]. These tools allow engineers to examine the environmental impact of different design alternatives (e.g. material substitution and weight optimization) during the design phase to facilitate the application of eco-design principles [13].

In this context many further improvements can be achieved through a rethinking of the design process by putting the eco-design activities (and the related tools) in the critical path of the design process. This can favour the creation of a new generation of design tools, fully-integrated in the traditional design process, where environmental considerations become a key factor when decisions on product are taken. This research work moves towards this goal [14].

The research activities want to make up for this lack and develops an eco-design methodology and a related software design tool able to assist product designers in ecological design choices, without losing sight of cost and typical practicalities of industry. The objective is to supply a platform completely integrated with the other main design tools (CAD/PLM).

The proposed approach has been applied to the household appliance field but it can be easily extended to other mechatronic products.

The final result, proposed within this work, is the creation of an integrated software platform will propose a guided process towards eco-design among several design choices based on the different scenarios of product lifecycle. The virtual product model can be automatically updated on the basis of environmental assessment results.

The developed tools and the integrated platform enable designers to evaluate different design alternatives easily and dynamically during the early product development phase. By this way it is possible to design green products taking into consideration the environmental lifecycle impact and also the lifecycle cost aspect of the product. A prototype of IT platform and industrial products highlights the benefits introduced by the application of the eco-design approach.

## 2 Research planning and activities

This research thesis aims to address the problem why eco-design and energy efficiency has not been more broadly adopted as a routine process within new product development. Eco-design approaches and tools are currently viewed as "tools for experts" and are not widespread in the design departments. Designers and engineers are focused, usually, to increase product performances and reduce manufacturing costs. Ecological aspects and energy efficiency problems are considered only for particular kind of products and the way to design and develop these products is not standardized. In order to be made useful the eco-design activities, they need further interpretation for an individual company business sector and product type.

*The first objective of this proposed work is to create a robust eco-design approach, fully-integrated in the traditional design process and able to support the designer choices for the evaluation of the direct and indirect consequences throughout the industrial product lifecycle.*

The proposed methodology is based on lifecycle engineering with the scope to increase the ecological and economic aspects of the household appliances during the entire lifecycle. A specific module has been developed with the scope to calculate easily and with few operations the main environmental indicators or product lifecycle parameters. Different phases occur during a product lifecycle: material extraction, manufacturing and assembly processes, transportation, use and final disposal. With the new eco-design method, all phases can be taken into consideration to improve the product in different ways. The keyword to be pursued is integration. Integration means considering all the aspects of the product lifecycle for a complete analysis of sustainability in the whole product lifetime. Integration is, also, the possibility to include the eco-design principles and guidelines in the traditional design process.

Two different levels of integration are developed for this purpose: *Vertical Integration* and *Horizontal integration* as proposed in Figure 1:

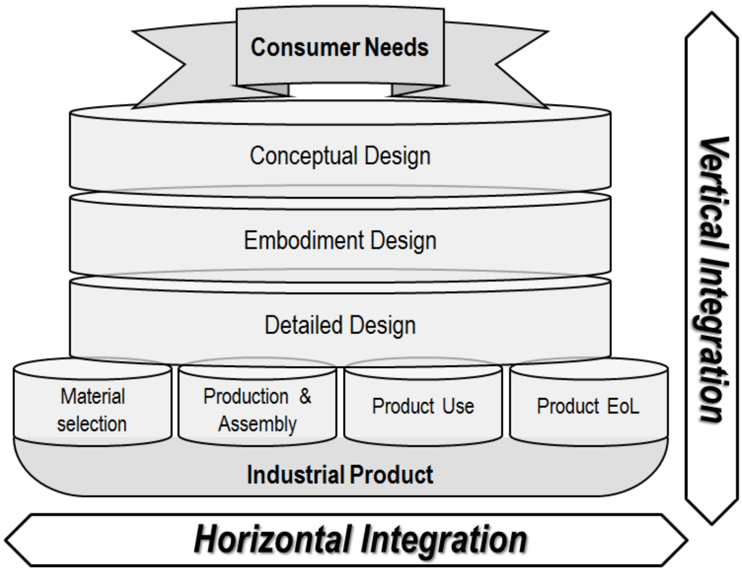


Figure 1: Vertical and Horizontal Integration for the eco-design systems in the product design practice.

For the implementation of this new eco-design method a list of halfway outcomes have been reached:

- Definition of environmental performance parameters considering product lifecycle. The most important instrument to describe the environmental behaviour of products and appliances is the measurement of environmental performances. In this way, designers are able to measure and compare product performances according to an established lifecycle methodology. Only few and indicative parameters are visible to designers in the first step of the design process when they are used to measure the values of lifecycle cost and environmental impact: *Energy consumption* [MJ], *Water consumption* [m3], *$CO_2$ emitted* [kg $CO_2$ eq.], use of *Natural resources* [EI99] and *LCC* [€]. Furthermore, new indices have been developed to measure new important performances to be considered for environmental analysis such as the product assemblability, feasibility of different EoL scenarios, energy efficiency, etc.
- Definition of the main lifecycle phases in terms of environmental impacts for household appliances, mechatronic products and product-services. The definition of lifecycle phases allows to formulate different product scenarios and to evaluate environmental impact throughout lifecycle. While developing the product, designers can quickly make decisions and determine lifecycle strategy for each component. The four phases considered in this approach have been defined: *Material extraction and Transformation* (1), *Component Manufacturing and Product Assembly* (2), *Product Use* (3), *Product End-of-life* (4).

*The second objective is the development of a set of eco-design tools which can guide the designers in the eco-sustainable choices in all phases of the product lifecycle.*

Eco-design tools can be able to calculate, manage and compare the results of the previously defined environmental parameters, and suggest solutions to the designers which can be adopted to increase the product sustainability. Several tools have been developed to reach this target and grouped in two main systems: tools to measure the economic and environmental lifecycle impacts of the product under analysis (grouped in the *Dynamic CAD Package System*) and tools to improve the sustainability of the product or product-services considering the whole lifecycle (grouped in the *Eco-design Gateway API*).

A schematic representation of the entire eco-design platform and the related software tools are proposed in Figure 2.

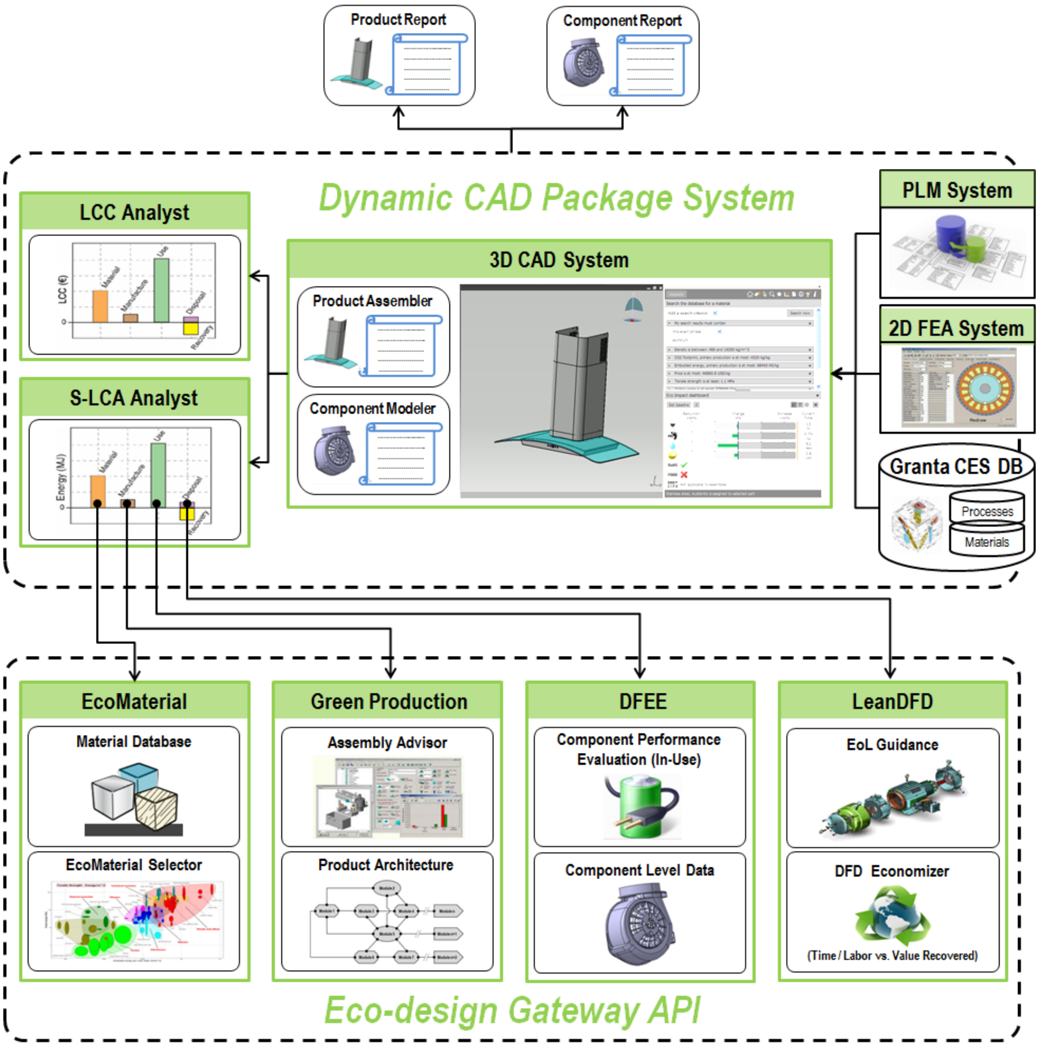


Figure 2: General framework of the proposed eco-design platform and related eco-design tools.

The core system of the entire platform is the *Dynamic CAD Package System* (*DyCAD*). The two tools of this evaluation system can calculate environmental parameters and the value of the cost spread in the whole product lifetime:

- The *S-LCA Analyst* tool evaluates the environmental impacts related to the product under analysis. Only a limited list of results derived from *S-LCA Analyst* tool is visible to the designers during the design stage to make easily and understandable the environmental performance and the possibility to do comparisons. These environmental parameters are the same defined above.

- The *LCC Analyst* tool evaluates the cost of the whole product lifecycle, called Life Cycle Cost (LCC). The LCC result is the sum of several items of cost which resulting in all lifecycle phases at different times. LCC value is associated with the costs of materials, the costs of manufacturing processes and assembly, the costs of transport, the costs of use related to energy consumption of household appliances and the cost of dismantling at EoL.

The other tools of the implemented system give an improvement to the specific phase of product lifecycle, but at the same time they are integrated together to support the whole design process of the product. This system is called *Eco-design Gateway API*. The eco-design tools have been realized on the basis of the main lifecycle phases previously defined: *Eco-Material*, *Green Production*, *DFEE*, *LeanDFD*. Each tool have been defined to be useful to simplify the designers' work and structured to reach, step by step, the solutions for the minimization of environmental impacts and the lifecycle cost. Guidelines can support the decision-making strategies of designers; a real-time change is available in the design model and data structure of the product. Each eco-design tool represents a possibility to increase environmental performances in the analysed phase of product lifecycle:

- The *EcoMaterial* tool evaluates more sustainable materials on the basis of embodiment energy needed for primary extraction and production, the exploitation of resources and minerals, the quantity of greenhouse gases emitted and the possibility of recycling.
- The *Green Production* tool determines not only the best production process associated with the material choice, but also a design step in order to reduce the number of components and their weight. A rule-based procedure aids the designers in applying the DFMA methodologies (Design for Manufacturing and Assembly) and therefore simplifying the product assembly process.
- The *DFEE* tool permits to improve the energy efficiency of particular components, such as the electric motors used in the household appliances. Electric motors, in fact, are the main responsible of electrical energy consumption during product lifecycle. The purpose of this tool is to develop dedicated electric motors which have very high electro-magnetic performances in order to reduce the electric energy consumption during product use and the related costs.
- The *LeanDFD* tool evaluates alternatives in connection systems between two or more components in a product to make easier the disassembly operations and reduce the disassembly time. An improvement in disassembly operations and time encourages the possibility for a selective disassembly of product components and at the same time increments the quantities of materials which can be recovered or recycled at product End-of-Life.

In addition, some other secondary aspects have been taken into account during the achievement of the described objectives, such as the high usability of the platform, the real integration within the CAD user-interface, the efficient data exchange among several tools and the good balance between consistency of environmental and economic lifecycle results and time efforts to make the analysis.

## 3 Analysis and discussion of main results

The eco-design approach and the IT software platform have been tested to support the activities of design departments in the product and product-service development oriented to sustainability. Different Italian companies 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 system.

The redesign activity has 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 new developed products and product-services have been considered innovative real solutions both in industrial and domestic fields.

### 3.1 Cooker hood product

Important outcomes have been reached by the implementation of the eco-design approach in the hood model. The environmental and LCC values are calculated considering a product working scenario of 7 years and a rate of 2 working hours per days. Electric motor, lamps and stand-by system are considered in the general assessment of energy consumption during cooker hood use.

The results are summarized in the Table 1.

Table 1: Comparison between the original design (O.D.) and the new design (N.D.) of a free-standing cooker hood model k7388.

| **FREE-STANDING COOKER HOOD (MODEL K7388)** | | | |
|---|---|---|---|
| *Lifecycle parameter* | | *O.D.* | *N.D.* |
| Number of used materials | | > 20 | < 12 |
| Component numbers | | 205 | 82 |
| Environmental | Equivalent $CO_2$ [kg] | 1222,5 | 725,7 |
| | Energy cons. [MJ] | 45e3 | 9,3e3 |
| | Natural resources [EI99] | 184 | 72 |
| | Water consumption [$m^3$] | 78 | 69 |
| Cost | LCC [€] | 4343,8 | 2798,2 |
| End-of-Life | $I_{EoL-Rc}$ | 6,2% | 38,5% |
| | $I_{EoL-Ru}$ | 1,1% | 16,8% |
| | $I_{EoL-Rm}$ | 3,2% | 7,2% |
| | $I_{EoL-Inc}$ | 0,6% | 0,6% |
| | $I_{EoL-Lf}$ | 84,3% | 31,1% |
| | $I_{EoL-Dt}$ | 4,6% | 5,8% |

The following Figure 3 highlights the different configuration of the original design (O.D.) and the new design (N.D.) of the same cooker hood model (k7388).

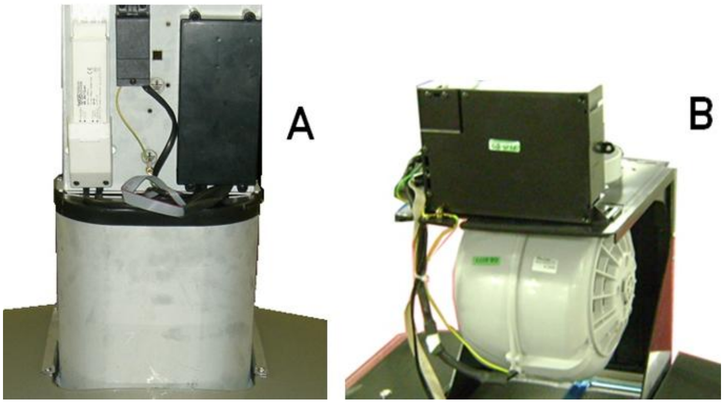


Figure 3: Original Design (A) and New Design (B) of the cooker hood model k7388.

The cooker hoods components are redesigned, manufactured and assembled with the purpose to test, in real world, the improvements carried out with the eco-design implementation.

Furthermore, the environmental parameters and the EoL indices give understandable metrics to assess the environmental and economic benefits of the proposed redesign. The general results are presented in Table 1. The main advantages reached with the new design solution are:

- the possibilities to recycle material (approx. 38%)
- the possibility to reuse some components (approx. 17%)
- the possibility to remanufacture some components (approx. 7%).

Therefore, for the hood lifecycle, more than 62% of product components can have a closed-loop lifecycle. There is an important, significant reduction in the percentage of EoL landfill waste with the new design of cooker hood compared to the old solution ($I_{EoL\text{-}Lf}$ 84.3% vs. 31.1%).

A detailed example of the improvement achieved for the *Electrical system support* module using *LeanDFD* tool to is reported in Figure 4.

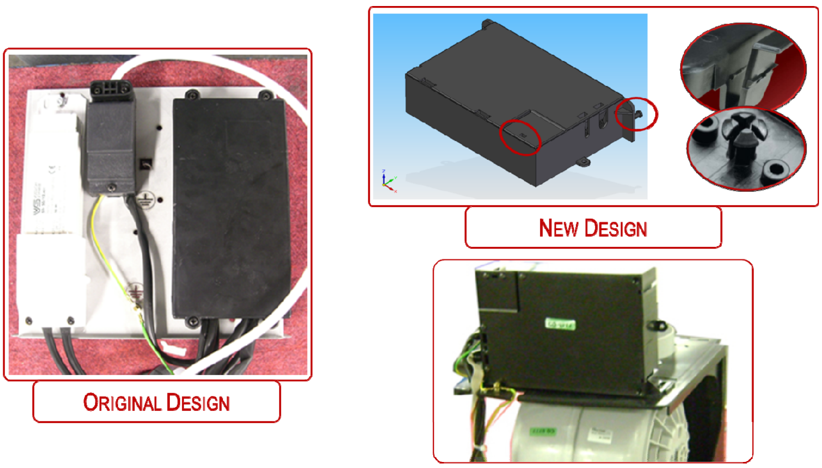


Figure 4: Solution adopted in the new design configuration of Electrical system and comparison with the original design.

### 3.2 Washing cycle product-service

The proposed case study is represented by an innovative idea in the household appliances context, in particular in the field of washing machines. The traditional product offer is based on selling the "washing machine"; the new product-service system is represented by selling "washing cycles", getting the machine as a loan for use. The latter is clearly a *Product2Service* solution (Figure 5).

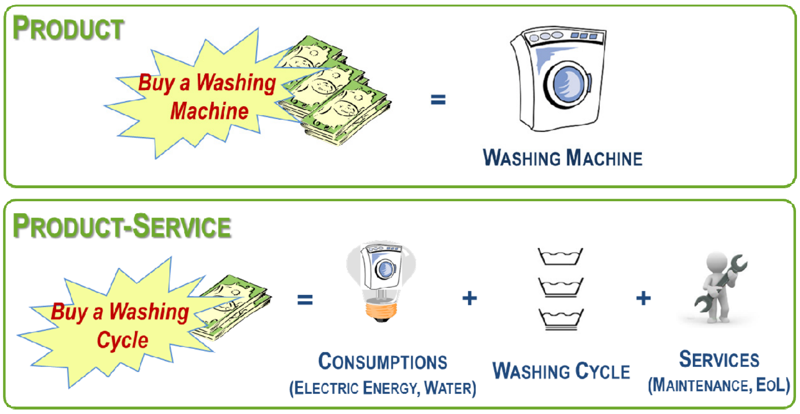


Figure 5: "Washing Machine" product vs. "Washing Cycle" product-service.

The proposed lifecycle approach is applied for the case study analysis and important results can be retrieved from the analysis of lifecycle parameters, as the possibility to compare the economic and environmental sustainability of product or the alternative product-service. This preliminary analysis demonstrates how the transition from the perspective of product to product-service system design gives important benefits in terms of environmental and economic sustainability in the whole lifecycle (Table 2).

Table 2: Comparison between Washing Machine (product) vs. Washing Cycle (product-service) lifecycle value for the eco-sustainability.

| WM PRODUCT VS. WM PRODUCT SERVICE (INDESIT COMPANY) | | | |
|---|---|---|---|
| *Lifecycle parameter* | | *Washing Machine* | *Washing Cycle* |
| Environmental | Equivalent $CO_2$ [kg] | 1044,6 | 889,9 |
| | Energy cons. [MJ] | 6,9e3 | 5,9e3 |
| | Natural resources [EI99] | 82,5 | 76,4 |
| | Water consumption [$m^3$] | 104e3 | 98e3 |
| Cost | LCC [€] | 1395,6 | 1271,2 |
| End-of-Life | $I_{EoL-Rc}$ | 53,8% | 63,5% |
| | $I_{EoL-Ru}$ | 4,9% | 7,1% |
| | $I_{EoL-Rm}$ | 4,2% | 10,4% |
| | $I_{EoL-Inc}$ | 1,6% | 0,4% |
| | $I_{EoL-Lf}$ | 32,3% | 14,5% |
| | $I_{EoL-Dt}$ | 3,2% | 4,1% |

## 4 Conclusions

The major contribution of this research work has been to establish a novel eco-design approach with the purpose to consider sustainable lifecycle aspects in the early phases of product development process.

A list of the main outcomes reached with the developed eco-design environment (approach and tools) are listed as follow:

- consider environmental impact without the need to develop expertise in the area or to hunt for the right eco-data
- address environmental requirements early in the design process when changes matter most and cost least
- design more sustainable, cost-effective, and durable products
- increase product sustainability and reduce the quantity of product waste
- customize products and product-service systems to reduce the environmental load and lifecycle cost.
- achieve competitive advantage through faster design innovation and more sustainable products
- clearly communicate the benefits of enhanced eco-sustainable products.

The fabrication of household appliances such as the cooker hood or component of mechatronic products such as the electric motor highlights the following benefits in terms of sustainability, environmental load and LCC reduction:

- ✓ reduction of Energy consumption approx. 30%
- ✓ reduction of CO2 emitted and Water Consumption approx. 20-25%
- ✓ reduction of use of Natural resources approx. 15-20%
- ✓ reduction of LCC approx. 40%.

The proposed case studies give an important result in terms of industrial waste reduction, encouraging the Recycling, Reusing and Remanufacturing of several components. The rate of EoL closed-loop scenario feasible for the analysed products and product services is approx. 50-60%.

A deeper research activity is necessary in the field of product-service systems which can be a possible solution to have a customized product lifecycle and a certified EoL scenario. In this way, manufacturing firms are encouraged to reduce or eliminate industrial waste due to the possible economic benefits can be achieved by the retirement of product at EoL.

New features can be added and considered to the eco-design approach such as the management of the supply-chain in both direction (direct and inverse supply-chain). Firstly, to manage the suppliers for the sustainable manufacturing of product components. Secondly, to retrieve the product at EoL and distribute the product components on the bases of the defined EoL options. The dynamics of the reverse supply chain and its ramifications could thus be studied as a potential research area. This area however falls into the broader context of environmental conscious manufacturing.

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