Eco-design teaching initiative within a manufacturing company based on LCA analysis of company product portfolio

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Abstract

Eco-design is the integration of environmental considerations within product design and development. Eco-design represents an important innovation driver for companies; however, well-known barriers limit the diffusion of this design paradigm in the industrial world. Amongst these, lack of eco-knowledge is correlated to the adopted eco-design teaching methods. Previous experience has highlighted that traditional teaching methods such as university lectures or refresher courses are not an effective means for disseminating eco-design knowledge in the industrial world.

In this context, the present paper proposes a novel eco-design teaching method based on a transformative strategy for promoting eco-design and facilitating the learning process.

This approach, tested in collaboration with an Italian manufacturing firm, is considered the first attempt to implement a repeatable eco-design teaching approach that can be scaled up in different industrial contexts. Several company departments, including management, marketing and commercial affairs, design and engineering, and a testing laboratory were involved in the training program. Technical results show that company employees were able to autonomously implement re-design solutions and improve the environmental performance of a coffee machine upon completion of the course. The quantitative evaluation of formative outcomes through assessment before and after the course highlights a significant increase in the awareness of personnel and knowledge relating to eco-design.

Keywords

Teaching; eco-design; life cycle assessment; eco-knowledge; product portfolio

Highlights

- Eco-design teaching method for industry and manufacturing companies
- Life cycle assessment of company product portfolio
- Eco-design tips for development of espresso coffee machines
- Success story for implementation of eco-design training in a manufacturing firm

1. Introduction

Eco-design is defined as ''the integration of environmental aspects into product design and development with the aim of reducing adverse environmental impacts throughout the whole product's life cycle” (ISO, 2011). Eco-design methods are widespread in academic and scientific literature and have been developed in response to sustainability policies adopted by national and international organizations (Dekoninck et al., 2016; Rossi et al., 2016; Favi et al., 2018). Environmental sustainability is being addressed positively within industry through the design and development of more eco-friendly products (Johansson, 2010). The demand for new products with intrinsic ecological features is driven by several factors: (i) national/international policies and legislation (van Hemel and Cramer, 2002; Bey et al., 2013; Pigosso et al., 2014; Iranmanesh et al., 2018), (ii) new opportunities from the market (van Hemel and Cramer, 2002; Bey et al., 2013), (iii) social responsibility of companies including improved brand value (van Hemel and Cramer, 2002; Bey et al., 2013; Iranmanesh et al., 2018), and (iv) economic and environmental outcomes (van Hemel and Cramer, 2002; Iranmanesh et al., 2018).

Despite the fact that adoption of eco-design strategies in product development can offer several advantages to industry, their effective implementation within technical departments seems difficult (Lindahl, 2006; Jabbour, 2015). Existing barriers against the diffusion of eco-design practices in industry have been identified in the literature by several authors. These barriers can be summarized as follows: (i) lack of designer and engineer knowledge in relation to environmental sciences (Bey et al., 2013; Neri et al., 2018; Pinheiro et al., 2018), (ii) lack of allocated resources for environmental analysis (man power and time) (Le Pochat et al., 2007; Bey et al., 2013; Jabbour and de Sousa Jabbour, 2016), (iii) lack of relevant/suitable methods and tools able to support eco-design initiatives (Lofthouse, 2006; Rossi et al., 2016, Favi et al., 2018), (iv) difficulties in trade-off analysis (cost, performance, environmental sustainability, etc.) (Bovea and Pérez-Belis, 2012; Dekoninck et al., 2016), and (v) difficulties in retrieving information about alternative materials and manufacturing processes with lower environmental impact (Hernandez Pardo et al., 2011; Morbidoni et al., 2011; Chun et al., 2018).

In relation to the lack of eco-knowledge and expertise, the employed eco-design teaching method plays a critical role for the effective implementation of eco-design strategies within industry. In particular, the possibility of gaining eco-knowledge in an industrial context comes from the development of dedicated projects (eco-innovation) or the development of specific training programs (eco-design courses, etc.). However, the common eco-design guidelines developed by several authors (Luttropp and Lagerstedt 2006; Knight and Jenkins, 2009) are too general to be effectively adopted in real case studies and do not provide a tangible tool for designers and engineers. Education of future generations of decision-makers in industry such as engineers, designers and managers is generally overseen by schools and academia with the aim of tackling sustainability challenges faced by society (Boyle, 2004; Cosme et al., 2018). Life cycle engineering principles have been adopted as a baseline for the development of engineering courses oriented towards eco-design and environmental sustainability (Luttikhuis et al., 2015; Olsen et al., 2018). This is a consolidated trend in engineering education, especially in European countries (Tejedor et al., 2018). For example, life cycle assessment (LCA) has become a new topic in the engineering sciences and is usually coupled with product development (Cosme et al., 2018). LCA is a well-established and widely accepted tool that can be used to determine the environmental profile of a product (ISO, 2006a; ISO, 2006b). Although the eco-design standard does not refer to LCA, the latter has been widely applied to monitoring materials/energy consumption and environmental pollution during product design and manufacturing (Romli et al., 2015). For this reason, LCA can be considered a suitable method for developing eco-design guidelines and implementing eco-design strategies within technical departments. Literature on pedagogical experiences and application of LCA teaching initiatives, however, is scarce and the results of these initiatives will become tangible only in years to come (Evans et al., 2017; Thürer et al., 2018).

Only a few isolated schemes oriented towards eco-design and LCA training initiatives in the industrial sector have been adopted over recent decades with the aim of introducing eco-design principles in technical departments of manufacturing industries (Daily et al., 2012; Riel et al., 2015; Margallo et al., 2018; Favi et al., 2019). The outcomes of these training programs demonstrate that traditional teaching methods such as university lectures or refresher courses are not efficient at disseminating eco-design knowledge in the industrial world. This concern encourages the adoption of transformative learning (TL) approaches (Leal Filho et al., 2018) and the use of innovative teaching methods such as e-learning (Azeiteiro et al., 2015), project/problem-based learning (PBL) (Wyness and Dalton, 2018) and learning-by-doing approaches (Riel et al., 2015). An innovative training method for engineers and practitioners is therefore needed to support companies in the use of eco-design practices in their daily activities (Navajas et al., 2017). In addition, the gap between academic and industrial settings is still an open issue due to the pragmatic approach of industry, which is mainly oriented towards solving specific issues related to their products with quick and innovative solutions.

Following analysis of the state-of-art, two research questions can be highlighted:

- Does eco-design teaching lead to in-depth understanding of eco-friendly products?
- Does eco-design teaching lead to re-designing industrial products to make them more eco-friendly?

The objective of this work is to set the basis for implementation of an efficient eco-design training program starting from the features of products created by a manufacturing enterprise (the company's product portfolio) and providing a general framework able to integrate cognitive skills (technical knowledge) with emotional/affective changes relating to environmental aspects. In particular, the paper describes a "success story" related to the implementation of an eco-design training program within an Italian manufacturing firm.

The teaching initiative was developed in compliance with learning outcomes set out by the company in question. Eco-design guidelines were developed starting from the interpretation of LCA results, including the technical evolution of products (e.g. materials, manufacturing processes and technology) over time. Company personnel involved in the activities were trained on eco-design through analysis of the environmental performance of their past design solutions adopted across the whole product portfolio. This initiative allowed the gap to be closed in both directions: (i) horizontally, from academia towards industry and, (ii) vertically, across different company departments. The main outcome observed at the end of the eco-design teaching method was the transformation of participants' frames of reference towards environmental consciousness, demonstrated by the decisions made during the assignment phase of the course (development of new product concepts). This result, typical of transformative learning, coupled with technical skills acquired in relation to eco-design, provided the participants with the desired level of eco-knowledge (both positive and negative) that could be put in place during future design and development activities. The proposed model can be adopted as a model for implementation of a repeatable "eco-design teaching approach", which can be scaled up to other industrial contexts and applications.

The paper is structured as follows. Section 2 details the theoretical framework that represents the basis of the eco-design teaching method. Section 3 describes the proposed methodology, including the context and motivation, cognitive and affective learning outcomes, data collection and interpretation methodology, and five steps of the proposed teaching method. Section 4 discusses implementation of the proposed teaching approach in an Italian manufacturer of espresso coffee machines. Section 5 reports research findings in terms of both technical outcomes and teaching approach effectiveness. Section 6 discusses the strengths of the teaching method against common barriers to implementation of eco-design in industrial contexts, as well as some limitations and weaknesses. Finally, section 7 concludes the paper by discussing the results and future outlook, including the ability to transfer the approach to other industrial sectors.

2. Theoretical framework

The proposed eco-design teaching methodology and the initiative dedicated to an industrial context are grounded on different theoretical roots such as education for sustainability/sustainable development, cognitive and affective learning domains, and transformative learning.

Education for sustainability/sustainable development (ESD) aims to develop *"competencies that enable individuals to participate in socio-political processes and hence to move their society towards sustainable development"* (Barth et al., 2016). ESD should provide learners with the right means to understand the problems with a holistic view (Kalsoom and Khanam, 2017), improve their knowledge of sustainability issues and transform their attitudes and behaviors (Pappas et al., 2013; Azeiteiro et al., 2015; Jorge et al., 2015). ESD initiatives applied to industrial contexts need to provide technical knowledge about eco-design strategies to reduce product/process environmental loads and transform the thinking of individuals and organizations (Bergeå et al., 2006). In other words, both the cognitive and affective learning domains need to be integrated.

Cognitive learning involves knowledge and intellectual skills associated with the three pillars of sustainability (social, economic and environmental) including their inter-relationship (Kollmuss and Agyeman, 2002; Kalsoom and Khanam, 2017). Cognitive learning refers to intellectual development. With reference to sustainability education, cognitive learning refers to development of higher order intellectual skills i.e. analyzing, evaluating and synthesizing (Bloom, 1956). Higher order skills are essential to address sustainability problems.

The transition to sustainability through TL approaches requires engagement of students/participants in non-formal activities, moving towards participatory education models (Robina-Ramírez and Medina-Merodio, 2019), multi-disciplinarity, inter-disciplinarity and trans-disciplinarity of courses (Paletta et al., 2019), as well as more practical projects (Tillbury and Wortman, 2004; Holden et al., 2008; Molderez and Fonseca, 2018). PBL or learning-by-doing student-centered approaches foresee organization of the learning process around projects (Rodriguez et al., 2015; Leal Filho et al., 2016). Problems and problematic situations are essential to stimulate students in understanding what they need to learn to find an acceptable solution (Klegeris and Hurren, 2011; Van Poeck et al., 2018). PBL motivates learners to obtain deeper knowledge on topics within the course, promotes critical thinking and contributes to the building of capacities for lifelong learning (Berchin et al., 2017). PBL strongly contributes to facilitate the learning process, but it is also a transformative strategy (Portimojärvi and Vuoskoski, 2006). Specifically, learning contracts, real world experiences, group projects, role play, case studies and simulations are considered effective methods for putting into practice transformative education by giving learners the possibility to directly apply the acquired knowledge and critically assess choices (Mezirow, 2002).

In relation to the abovementioned framework, the eco-design teaching method aims to develop the cognitive skills of participants. Several initiatives/elements, characterizing each step of the proposed teaching method (reported in section 3.4), were included to engage students/participants in the building of technical knowledge.

In "Introductory lectures", basic concepts of eco-design were provided to participants through examples of eco-design projects in the same or other industrial contexts (content, development and elaborated communication) including benefits and avoided problems connected with the environment. In this step, self-reflection and classroom debating sessions were used to stimulate the emotional participation of participants.

In the "LCA of products", the company's product portfolio was analyzed by through LCA. Teachers defined the key aspects of LCA methodology (i.e. functional unit, goal, scope, and system boundaries) in compliance with ISO standards and product features. In this step, the building of specific knowledge in relation to the product and environmental issues was reached through the active involvement of participants in data collection.

In the “eco-design course”, several initiatives/elements to implement a transformative pedagogy were introduced, such as the working group sessions moderated by environmental experts, assessments (pre- and post-tests) and dedicated lectures with critical reflection of working activities (design actions, management decisions, marketing strategies, etc.) used to explore participants’ experiences and frames of reference about environmental issues.

In the “assignment”, a group exercise was adopted to apply the eco-knowledge gained in previous sessions to a real product with collaborative tasks.

Finally, in the “outcomes” phase, the critical analysis of results was debated through review sessions and structured plenary assemblies involving all participants and the experts that have taken place during the course.

3. Methodology

The following sub-sections describe: (i) the context and main reasons pushing companies to undertake eco-design (sub-section 3.1), (ii) learning outcomes (sub-section 3.2), (iii) data collection and interpretation methodology (sub-section 3.3), and (iv) the eco-design teaching method, together with details relating to its five steps (sub-section 3.4).

3.1. Context and Motivation

The implementation of an eco-design teaching strategy requires preliminary identification of the relevant context in which the company operates. Only in this way can the most suitable learning outcomes and most appropriate course organization be defined to maximize both technical outcomes and eco-knowledge. Generally, the context refers to two different and correlated domains: *external* and *internal*.

The *external domain* includes aspects falling “outside company boundaries”. These are mainly related to the environment in which the company operates, including markets served by the company and external stakeholders directly or indirectly related to the company. In relation to the eco-design teaching initiative, the external domain must be considered for the definition of the following aspects:

- type of eco-design strategies to adopt. Even if the company’s strategy relating to sustainability is usually internal, it is directly influenced by several factors belonging to the external domain, including product category/classification, market requirements, company brand positioning, etc. Different drivers affect the choice of eco-design strategy such as customer demands, specific legislation (e.g. European ecolabel directives for energy related products) and marketing (brand value);
- type of life cycle analysis to use. This depends on the product category/classification that defines the most suitable type of analysis (e.g. full-LCA, carbon footprint, water footprint) and indicators to consider for the measurement of environmental sustainability performance.

The *internal domain* includes aspects falling “within company boundaries”. An essential item to consider in this regard is the mission of the company in relation to environmental sustainability issues. Depending on the company’s long-term strategy, eco-design and teaching activities can be organized and implemented in different ways.

The internal domain also includes the definition of internal human resources to be involved in the teaching initiative. Eco-design is a complex activity that cannot be effectively carried out as an isolated process. Due to its nature, it must involve an interdisciplinary team comprising people with different backgrounds. Managers must steer choices to follow the company’s long-term strategy. Marketing/commercial personnel must understand market requirements relating to environmental issues (e.g. customer awareness) and set the most effective commercial strategies (e.g. marketing campaigns and prices). Technical employees must implement and verify technical solutions (e.g. material changes and adoption of different manufacturing processes) to improve product sustainability. It is therefore clear that eco-design teaching activities must be implemented by involving several people from different company departments.

Finally, the number and type of products to consider during activities must be chosen to complete definition of the internal domain. Generally, a representative group of products from within the company product portfolio should be analyzed during teaching activities. In this way, it is possible to analyze a large number of cases and technical solutions and define the best (positive) and worst (negative) practices to be used or avoided for future eco-design projects.

3.2. Learning outcomes

According to the European Credit Transfer and Accumulation System (ECTS) Users' Guide 2015 (ECTS, 2015), learning outcomes can be defined as *"statements of what the individual knows, understands and is able to do on completion of a learning process"*. As explained in section 2, the proposed teaching method affects both the cognitive and affective domains, thus learning outcomes for both domains have been defined.

Concerning the cognitive domain, the taxonomy proposed by Bloom (1956), and subsequently revised by Anderson et al. (2001), has been used as a framework to define the learning outcomes and classify them according to the Bloom cognitive levels. As reported in Table 1, the defined cognitive learning outcomes cover the entire hierarchy from retrieving and remembering basic concepts about environmental sustainability to reusing acquired eco-knowledge. Since the present method is focused on industry and was developed in strict collaboration with an industrial company, learning outcomes were more heavily focused on higher levels with the aim of training company employees to autonomously solve future eco-design problems at the end of the course.

Table 1. Learning outcomes of the Eco-Design Course.

Learning outcome	**Bloom's cognitive level**
1. State and explain the basic concepts of life cycle thinking approach and LCA methodology	I – Remembering
2. Identify the most important and critical life cycle phases in the specific industrial sector	II – Understanding
3. Use design information to build a product life cycle model	III – Applying
4. Compare different design alternatives from an environmental point of view	IV – Analyzing
5. Select the most appropriate design solutions according to traditional drivers (e.g. cost, performance) and environmental drivers	V – Evaluating
6. Define eco-design guidelines based on product LCA outcomes	V – Evaluating
7. Design/re-design new/existing products to improve their eco-sustainability	VI – Creating
8. Interpret and use results during negotiation phase	VI – Creating
9. Use the acquired knowledge to train other employers	VI – Creating
10. Recall eco-design tips in the conceptual design of new products	VI – Creating

3.3. Data collection and interpretation

The data were collected through pre- and post-tests. The test contained multiple choice items, true-false, short questions and matching items. The test aimed at measuring participants':

- life cycle thinking and life cycle assessment of energy-related products;

- materials and manufacturing processes used to produce the analyzed products;
- product use;
- product end-of-life management.

The assessment was designed based on the framework provided by Bloom's taxonomy and was consistent with the expected learning outcomes (Bloom et al., 1956; McKeachie and Svinicki, 2013). Twenty-four questions were defined comprising twenty closed-ended questions and four open-ended questions, as reported in Appendix A. The criteria used for evaluation of the answers followed guidelines provided by Worthen et al. (1993) and is described in Table 2. For closed-ended questions, the following criteria for scoring was adopted: (i) correct answer = 3 points, (ii) wrong answer = -1 point, and (iii) no answer = 0 points. A scoring system with negative marks for wrong answers was chosen to discourage participants from guessing and thus increase test reliability and validity (Burton, 2004). Due to the subjectivity of evaluating open-ended questions, the score in this case ranged from a minimum of 0 points for no answer to a maximum of 5 points for a complete and detailed answer. A maximum score of 80 points could therefore be obtained for each test, comprising 60 points for closed-ended questions and 20 points for open-ended questions. Finally, the score was translated into a mark from 1 to 5 based on the following scheme: (1) Insufficient, (2) Sufficient, (3) Good, (4) Very good, and (5) Excellent. In this case, a maximum mark of 3.75 could be achieved from closed-ended questions and a maximum of 1.25 could be achieved for open-ended questions. Open-ended questions and closed-ended questions accounted for 25% and 75% of the final mark, respectively.

Table 2. Structure of the assessment and marking scheme.

Type	**Number of questions**	**Criteria**	**Maximum score**	**Maximum mark**
Closed-ended questions (multiple-choice, true or false, matching)	20	Correct answer = 3 pt.	60 [pt]	3.75
		Wrong answer = -1 pt.		
		No answer = 0 pt.		
Open-ended questions (short answers)	4	5 pt. max	20 [pt]	1.25
			Tot = 80 [pt]	Tot. = 5

Open-ended data were coded and clustered into predetermined categories: (i) eco-design actions (questions 21 and 23), and (ii) environmental concerns related to design choices (questions 22 and 24). This classification enabled measurement of pre- and post-test levels of eco-knowledge (i.e. in which phase of the life cycle were more eco-design actions focused) and to verify the efficiency of the proposed training method.

3.4. The eco-design teaching method

According to PBL and learning-by-doing principles, the proposed teaching method is mainly based on directly involving company employees during various phases. After preliminary lectures aimed at formalizing basic eco-design concepts to achieve a common level of eco-knowledge, company personnel support eco-design experts in specific tasks by providing useful information or revising choices. Company employees are then called upon to become the main actors of the training program within an eco-design project team.

The workflow and main activities of the teaching method spanning 12 months are illustrated in Fig. 1. Details of each step are reported in the following sub-sections.

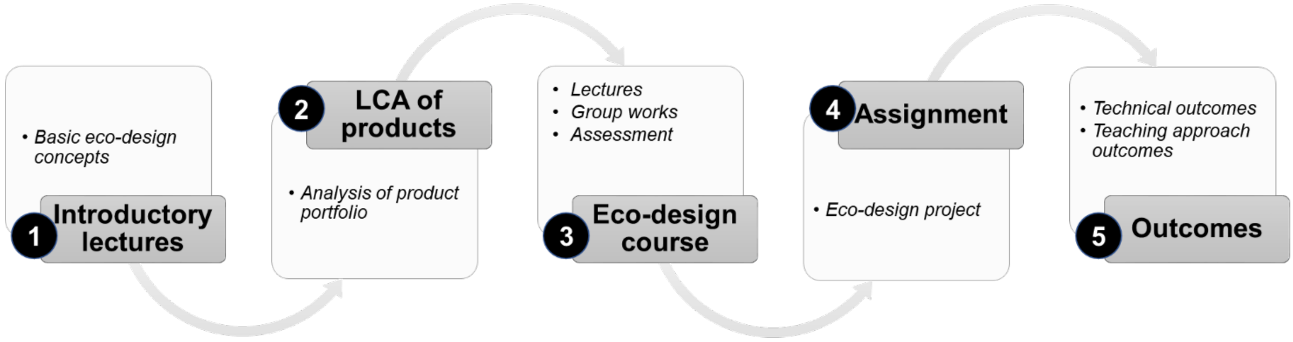

Fig. 1. Steps in the proposed eco-design teaching method

3.4.1. Introductory lectures (Step 1)

Introductory lectures are required to explain issues relating to design for environment and to provide all involved employees with the basic concepts of eco-design, life cycle engineering and LCA. The duration of the initial phase is limited to 6 hours (three 2-hour lectures) over 1 month. Lectures focus on explanation of the following concepts:

1. context and environmental standard/legislation relating to the considered industrial sector or market;
2. life cycle thinking, with particular focus on the concept of product lifecycle and how it can be taken into account during the design process;
3. basic concepts of LCA methodology and tools.

3.4.2. LCA of products (Step 2)

During the second step, LCA analysis of selected products is performed by following the four-step methodology described within ISO 14040 and ISO 14044. Environmental experts are the main actors during this phase, while internal personnel from different company departments are actively involved in supporting specific tasks within the LCA study. This is the longest phase of the entire course and can span several months (generally 4-5 months). Its duration, however, is not fixed and strongly depends on the number and complexity of the analyzed products.

Essential aspects to be defined at the beginning of any LCA study include the functional unit and system boundaries. Their definition is strongly affected by both the internal and external domains within the given context. The functional unit can be defined by considering the products and context in which they are used. In the same way, system boundaries are strictly correlated to product characteristics and company sustainability targets.

Depending on the complexity of the selected products, a huge amount of information and technical documentation (e.g. 3D models, drawings and a bill of materials) must be analyzed during the life cycle inventory phase. The support of company personnel with thorough knowledge of the products is therefore essential for collection and classification of all relevant data. Both the employees involved in training, as well as those in charge of managing product-related information (e.g. supplier data, material types not explicitly reported in the bill of materials, manufacturing processes and maintenance plans) are called on to be active participants.

During the life cycle impact assessment phase, selection of the most suitable environmental indicators (e.g. global warming potential, human toxicity, ozone depletion and/or acidification potential) is strictly related to the characteristics and specific needs of the product portfolio under analysis (context).

3.4.3. Eco-design course (Step 3)

The direct involvement of company personnel in specific tasks in Step 2, together with introductory lectures in Step 1, contribute to stimulating company employee awareness of common issues that must be faced, data that must be collect and aspects that must be considered during environmental assessment of an eco-design project. After completion of all LCA studies, the third step focuses on providing company employees with additional advanced skills relating to eco-design and environmental sustainability to allow them to independently develop and manage future projects. The duration of the eco-design course is limited to 30 hours over 2 months (4 hours per week on average).

The course mainly focuses on analyzing and discussing, in detail, results obtained from the LCA of selected products. The final aim is to derive specific eco-knowledge relating to the analyzed products and, more generally, relating to the considered product category or industrial sector, to provide the involved personnel with useful best practices to reuse in the case of new or variant designs.

The course is structured as follow:

- A series of lectures focused on the explanation and critical review of results obtained from the LCA (about 80% of the course duration);
- One or more group activities organized to demonstrate how it is possible to apply the acquired knowledge to resolving practical problems (about 10% of the course duration);
- Assessment taken by participants to verify their understanding (about 10% of the course duration). An initial test has the objective of classifying participants on the basis of their eco-knowledge, while a final test is performed to verify both individual and group progresses.

3.4.4. Assignment (Step 4)

At the end of the course, an assignment is given to the involved personnel to test the effectiveness of the teaching method. This is focused on the development of an eco-design project aimed at improving the environmental sustainability of an existing product. During this phase, company employees are required to re-design a future version of the coffee machine with eco-design features. The duration of the assignment lasted 3 months, but can be customized based on the complexity of the product and eco-design project. During this step, environmental experts act only as support during the most difficult phases in strict collaboration with company management to steer the project towards the best design solutions.

3.4.5. Outcomes (Step 5)

The last phase consists of the evaluation and discussion of outcomes obtained through implementation of the eco-design teaching method. Both technical and formative results must be assessed to obtain a comprehensive overview of the teaching method effectiveness.

From a technical point of view, the assessment mainly consists of evaluating whether the objectives of the eco-design project, set up during Step 4, have been fully satisfied. Specifically, the same environmental indicators chosen in Step 2 are used to compare the original and new design solutions. By measuring the obtained environmental benefits, it is possible to quantify the technical effectiveness and usefulness of the teaching method. It is worth noting that the external environmental experts play a central role during this phase in assessing the environmental sustainability of the innovative solutions with a new LCA study, comparing results with those obtained in the study carried out during Step 2.

In relation to the effectiveness of the teaching method, this can instead be quantitative measured through assessment, to be completed by the involved company personnel at the beginning of the course and after completion of the eco-design project. This tool allows measurement of the level of eco-design knowledge and how this evolves during the training program. An assessment criterion must be chosen to evaluate the answers. The final aim is to compare the test results obtained before and after the training course to verify three main aspects: (i) the level of eco-design knowledge, including the improvement of involved personnel, (ii) the ability to apply knowledge taught during the course, and (iii) the ability to draw a single conclusion from different inputs (convergent thinking).

4. Implementation of the eco-design teaching method

The proposed eco-design teaching method was implemented in an Italian industrial company involved in the production of coffee machines and coffee brewing products. After definition of the context, the method was trialed by following the methodological steps described in the previous section.

4.1. Professional espresso coffee machine context

In relation to the external domain of the company involved in the eco-design teaching project, the type of eco-design strategy to adopt was determined on the basis of three main inputs. Firstly, it was necessary that the company was compliant with current European regulations for coffee machines (i.e. directives for eco-design and waste of electrical and electronic equipment). Another important aspect related to the growing environmental awareness of certain markets served by the company. Finally, the company acts as a supplier to important coffee shop chains (e.g. Starbucks and McCafè), which are particularly attentive to environmental sustainability as reported in their corporate responsibility reports. These large companies are involved in continuously improving the sustainability of their products in terms of both their internal actions and the entire supply chain. All supply chain partners are therefore required to provide sustainable materials/products and quantitatively demonstrate their improvements with concrete eco-design actions and LCA indicators.

Due to the technical nature of professional espresso coffee machines and their consumption of electrical energy during use, the global warming potential (GWP) indicator calculated with the IPCC method (IPCC, 2007) was adopted as a single-issue indicator for the LCA analysis. GWP is a widespread and largely accepted indicator for energy-related products, as reported in several state-of-the-art research works (Brommer et al., 2011; Hicks and Halvorsen, 2019). It is considered mandatory for monitoring this type of product in international and European directives (EU, 2009). Moreover, this indicator is widely used in most industrial sectors and is considered understandable by a wide audience and non-expert stakeholders.

In terms of the internal domain, eco-design activities were structured based on guidelines provided by the top management of the involved company, who decided to adopt a systematic strategy with the objective of improving the environmental performance of the entire product portfolio. This initiative was the first of its kind oriented towards eco-design of products and capitalization of eco-knowledge. For this reason, continuous collaboration with eco-design experts from academia was adopted, avoiding isolated consultancy services. The company's strategy was to undertake a learning process to provide eco-knowledge for internal employees.

Another relevant aspect within the internal domain was the human resources involved in the eco-design teaching activities. In the present case study, eleven people belonging to four company departments were involved:

- two managers from *company management*;
- two employees from the *marketing department*: the marketing director and an employee with 10 years' experience, responsible for the North American market;
- five employees from the *design and engineering department*: the technical director, two mechanical engineers with 15 years' experience, one junior mechanical engineer with less than one year's experience and one electronic engineer with 8 years' experience;

- two employees from the *testing laboratory*: an engineer who headed the internal laboratory and a technician with 2 years' experience.

Finally, the number and type of products to analyze were chosen at the beginning of the project together with company management (Table 3). The selection process was driven by the following criteria:

- to cover both low and high-end markets;
- to cover all of the most demanding markets in terms of environmental issues, including Northern Europe, the United States and Japan;
- to cover all product types, including not only coffee machines but also grinders;
- to cover at least 70% of the sales volume.

Table 3. Products analyzed during eco-design teaching activities.

Product type	**Market type**	**Product model**
Professional coffee machine	High-end	VA 388 
		VA 358 
	Low-end	Aurelia II 
		Appia II 
Automatic coffee machine	Hotels / Canteens	Prontobar 
Coffee grinder	Low-end	Mythos I 
	High-end	Mythos II 

4.2. The eco-design teaching method in practice

This sub-section describes how the first four steps of the method were practically implemented through the involvement of a coffee machine producer. The last step (Step5 – Outcomes) is detailed in section 5.

4.2.1. Introductory lectures on eco-design in the coffee machine sector

Since this study was the first eco-design activity for the company involved, the global level of eco-knowledge was low at the beginning. Only the junior mechanical engineer had some basic skills relating to eco-design acquired during university studies. The introductory lectures were therefore essential for providing all participants with basic knowledge relating to eco-design. Other than generic lessons on life cycle thinking and LCA methodology/tools, the first step of the teaching activities was focused on explaining the context and European and International legislation relating to electric/electronic appliances, particularly coffee machines. For instance, the European WEEE and eco-design directives were analyzed to understand which main aspects affect the design/re-design of new/existing products.

4.2.2. LCA of coffee machines and grinders

LCA of the products was a complex and long activity due to the fact that all of the analyzed products, especially the four professional coffee machines, had a high level of complexity. Professional coffee machines comprise hundreds of components and/or assemblies (e.g. pumps, brewing groups, electronic control boards and frame), which are manufactured using a large number of materials (e.g. different types of steel, copper, brass, aluminum and plastic) and processes (e.g. metal shaping, casting, machining and plastic injection molding). For the products under consideration, most of the components were supplied by external companies, thus the supply chain was also rather complex. Performing an LCA of these products required direct involvement of internal personnel (application of the learning-by-doing approach) who had thorough knowledge of the products and thus supported the environmental experts during different phases of the study.

The environmental experts carried out the LCA study in compliance with ISO 14004 and ISO 14044. The Simapro 8.0.5.13 software tool equipped with the Ecoinvent 3.1 database was used to model the life cycle of the different products and calculate results in terms of the chosen impact category.

Company management was involved in defining the main objectives of each analysis (e.g. understanding the environmental performance of products and identifying the most relevant critical issues), while the marketing department was involved in identifying the most appropriate manner with which to communicate the results internally and externally. Based on the identified external domain (i.e. the market), the GWP indicator (IPCC, 2007) was adopted to quantitatively measure the environmental sustainability within the coffee machine sector and disseminate the results. Coffee machines and related equipment consume electrical energy during their lifecycle, with the most critical phase being use of the product itself. It was expected that use of the product would account for more than the 80-90% of the total environmental impact. As such, the GWP indicator was considered as most suitable.

Considering the internal and external domains comprising the relevant context of the involved company and sector, the functional unit for performing each analysis was defined as "the preparation of hot coffee, tea or milk-based drinks with a lifespan of 5 to 7 years in Italy and the United States considering three different use scenarios (low, medium and intensive)". Company management and the marketing department also played key roles during this phase in supporting the activities of the environmental experts.

Collaboration between the external experts and all of the involved internal departments, including company management, allowed definition of the most appropriate system boundaries for the LCA study. The manufacturing phase was taken into consideration due to the fact that the company designs and assembles all of their products internally. The use phase was considered as this is known to be the life cycle phase of greatest environmental impact for all energy related products (ErP). Finally, product end of life (EoL) was considered since all products were required to be compliant with the WEEE directive and other related standards (EU, 2012; IEC, 2012). Based on this directive, a certain percentage of materials used to manufacture professional coffee machines must be recycled at the end of their life. Specifically, the following assumptions were made based on technical documentation and statistical analyses: (i) approximately 60 % recycling of steel-based components, (ii) approximately 85 % recycling of aluminum alloy-based components, (iii) approximately 55 % recycling of copper-based components, (iv) approximately 10 % recycling of plastic-based components, (v) recycling of electric and electronic components based on WEEE directive performance, and (vi) other materials going to landfill (EC, 2015). In addition, the company planned to reorganize its business model by implementing actions aimed at directly managing the product EoL. In particular, they were to directly collect used products in the medium-long term, restore product/component functionalities and sell them as remanufactured goods in the low-end market. For this reason, a cradle to grave approach was chosen to provide a global view of the entire lifecycle.

During the life cycle inventory phase, the design and engineering department played a fundamental role in supporting environmental experts in the collection of relevant data relating to materials and manufacturing processes. In addition, partners of the supply chain were also involved in retrieving useful information relating to commercial components such as the boiler.

In relation to the definition of use scenarios and energy consumption data, no measurement protocol from international standards is available for coffee brewing equipment. A standard protocol is necessary to measure the energy consumption of these products in different working conditions (e.g. during coffee extraction, in stand-by, during the supply of hot water or steam). At first, the marketing and commercial departments were involved in defining a set of standard use scenarios for the most important markets served by the company (Italy and the United States). Different drink variants were defined based on the type of end-user (e.g. small bars vs. large coffee shops) and their geographic location (e.g. hot milk-based drinks are mostly consumed in United States while single shot espresso coffees are mostly consumed in Italy). Subsequently, the laboratory department was involved in defining a standard protocol to measure the relevant quantities needed for the LCA study, such as energy consumption during standby, coffee brewing and water heating. Finally, the protocol was applied to collecting relevant data for each product in Table 3 and each use scenario. The measured data were then used to derive daily, yearly and life cycle energy consumption profiles, as well as the energy consumption of each operational phase (e.g. warm up) and drink (e.g. preparation of a cappuccino), which were then applied to building an LCA model for the use phase. As an example, Table 4 reports use scenarios defined for Italy and the United States in cases of intensive and medium use.

Table 4. Italian and United States use scenarios.

	Italy 		**United States** 	
	Intensive	**Medium**	**Intensive**	**Medium**
Coffees per hour [N°]	40	24	2	2

Cappuccinos per hour [N°]	16	12	40	28
Teas per hour [N°]	6	6	1	1
Warm up cycles per day [N°]	1	1	1	1
Working time per day [h]	18	12	18	12
Lifetime [years]	5			

4.2.3. Course on eco-design of coffee machines

The course on eco-design of coffee machines, defined in line with indications given in Step 3 of the methodology, was followed by employees from the marketing and commercial, design and engineering, and laboratory departments (see section 3.1). Table 5 reports details relating to the type of lesson, duration and contents.

Table 5. Course outline.

Lesson	**Content**	**Type**	**Duration [hrs]**
1	Initial assessment	Test	1
2	Life cycle analysis of professional coffee machines	Lecture	5
3	Comparison of different coffee machines	Lecture	3
4	Life cycle analysis of coffee grinders and automatic coffee machines	Lecture	2
5	Comparison of different coffee grinders	Lecture	1
6	Detailed analysis of the manufacturing phase and comparison of design solutions (e.g. materials, lightweight design)	Lecture	6
7	Detailed analysis of the use phase and comparison of technologies (e.g. insulation of boilers) and use scenarios (e.g. Italy vs. United States, intensive vs. low use and influence of the stand-by phase)	Lecture	6
8	Detailed analysis of the EoL phase and comparison of EoL scenarios (e.g. recycling vs. remanufacturing)	Lecture	2
9	Framework for the re-design of a coffee machine	Group work	3
10	Final assessment (after Step 4 – Assignment)	Test	1

Based on the LCA results presented during lectures, several best practice design guidelines dedicated to coffee machines were defined during lessons 2 – 9. These guidelines, representing an output of the eco-design course (Step 1), were used by company employees during the subsequent eco-design project assignment to define and implement the most appropriate re-design strategy. An extract of the specific guidelines, together with the affected lifecycle phases, are reported in Table 6.

Table 6. Extract of specific guidelines for coffee machine eco-design.

Guidelines	**Lifecycle phase**
Energy efficient technologies shall be used to reduce overall energy consumption	Use
Insulation measures shall be adopted to reduce heat dispersion in boilers and pipes	Use

Smart sensors and technologies shall be adopted to reduce stand-by consumption (e.g. automatic switch off)	Use
Electronically controlled electric motors shall be adopted to regulate power absorption	Use
Aluminum alloys have a higher environmental impact than other materials (e.g. carbon steel) but have a higher recyclability ratio	Manufacturing, End of life
Stainless steels have a higher environmental impact and where possible must be substituted with carbon steel	Manufacturing
Plastics are lightweight materials but their recycling at the EoL is challenging	Manufacturing, End of life
Component weight and thus the quantity of material used for their manufacturing must be minimized	Manufacturing
The use of different types of plastic shall be avoided to favor product recyclability at the EoL	End of Life
The use of varnished parts shall be avoided to limit environmental issues related to manufacturing and the EoL	Manufacturing, End of life
The number of threaded joints shall be reduced in the external chassis to improve the reachability of internal parts	Maintenance, End of life
Rapid joint solutions shall be adopted to favor easy disassembly of components that must be subject to maintenance during the useful life of the device or are candidates for reuse/remanufacturing at the EoL	Maintenance, End of life

4.2.4. Re-design of the "Aurelia II" coffee machine

The assigned eco-design project was focused on the professional coffee machine model "Aurelia II" (see Table 3) with the following main specifications:

- external dimensions: 815 x 565 x 565 [mm];
- group heads: 2;
- copper boiler capacity: 14 [L];
- total nominal power: 4.5 [kW];
- digital pressure switch;
- volumetric pump;
- two steam wands;
- one hot water wand;
- electric cup heater;
- mixed stainless steel and plastic chassis.

The objective of the case study was to improve the environmental performance of the product while maintaining the same functionalities. Only a small increase (maximum +5%) in production cost compared to the original solution was considered acceptable, in line with management and marketing indications.

Other than traditional design data (e.g. CAD models and the bill of material), available input data were essentially the results of the full LCA carried out by the environmental experts in Step 2. In particular, the main environmental hotspot was related to the use phase, which was responsible for about 95% of the overall life cycle impact (considering the Italian use scenario, intensive use). Analyzing energy use in detail, about one third of total energy consumption was due to non-value-adding activities including warm-up at bar opening and stand-by between the preparation of one drink and the next. In relation to materials and manufacturing (total environmental impact of about 390 [kg CO_2eq]), the most important contributions were due to the following groups: (i) brewing groups: 55 [kg CO_2eq]; (ii) frame: 51 [kg CO_2eq], and (iii) main boiler: 48 [kg CO_2eq]. These results, together with the best practices defined during Step 3, constituted the eco-knowledge that guided the involved personnel in product re-design.

5. Research study findings

Results of the proposed eco-design teaching approach are described in this section. In particular, two different findings are reported: (i) technical results discussing the main eco-design solutions developed for new design of a professional coffee machine (section 5.1), and (ii) teaching approach results addressing the level of eco-knowledge shared within the company due to implementation of the eco-design teaching approach (section 5.1).

5.1. Technical results

During the assignment period, the different company departments involved in eco-design training worked as a team to re-design the “Aurelia II” coffee machine, finding several solutions to reduce the environmental impact. Re-design activities were mainly focused on reducing energy consumed during the use phase, since this was the most critical environmental hot-spot. The manufacturing phase was nonetheless considered, with several alternative material/design configurations implemented.

The first solution implemented in the new coffee machine was the adoption of T3 (three-dimensional temperature control) technology (Fig. 2). The “Aurelia II” coffee machine was originally equipped with Digit technology comprising a single main boiler (14 liters) and a digital pressure switch that allowed the operator to control the temperature within the single boiler through a digital user interface. T3 technology was instead based on the adoption of two additional small boilers located near the brewing groups, allowing control of the temperature in three different places: the main boiler, secondary boilers and brewing groups. During coffee brewing, only a small amount of water contained within the secondary boilers was to be warmed up to the required temperature (approx. 97°C), while the temperature within the main boiler was to be lower (approximately 80°C). As a consequence, the overall amount of energy required to brew coffees was largely reduced.

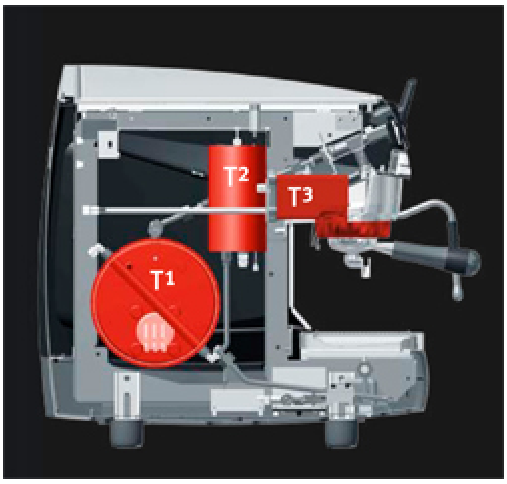

Fig. 2. Schematic representation of T3 technology

Despite the additional environmental impact caused by the manufacturing of two secondary small boilers, the overall dimensions of the main boiler could be reduced, thus reducing the overall amount of material used for its manufacturing. In addition, it was possible to adopt a smaller resistance for the main boiler (from 1 [kW] in the original version to 700 [W] in the re-designed version). This led to a significant reduction in the energy consumption for coffee brewing, approximately 35%.

Another solution that was implemented was insulation (Fig. 3) of all components where heat dissipation was relevant, including the main boiler, secondary boilers, brewing groups and pipes. The adopted insulation material was a polyammide-6 based foam with low density (52 [kg/m^3]), good resistance to high temperatures (up to 205 °C), and very low thermal conductivity (0.0420 [W/m·K]). The insulation reduced the overall electric energy consumption by approximately 4%.

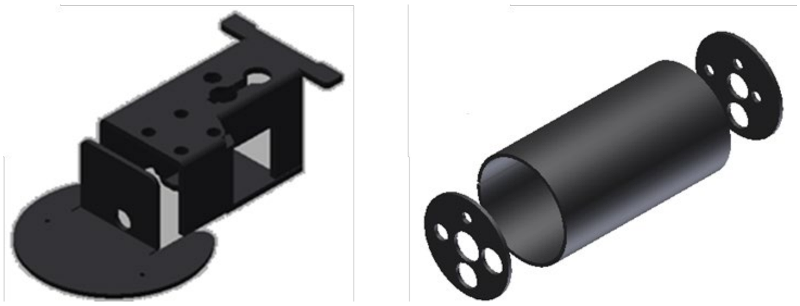

Fig. 3. Virtual models of insulation for the brewing group (right) and secondary boiler (left)

In relation to product manufacturing, the first design change related to the base of the frame assembly. This component was originally manufactured in carbon steel. Considering the fact that this component has no structural function, application of eco-design best practices ("component weight, and thus the quantity of material used for their manufacturing, must be minimized") led the design and engineering department to produce the base in acrylonitrile-butadiene-styrene (ABS) plastic. On the one hand, this resulted in reduction in the weight of the component from 3.1 [kg] to 0.4 [kg], with a consequent reduction in environmental impact relating to its manufacturing (-7,7 [kg CO_2eq]). On the other hand, the use of ABS with a lower recyclability partially reduced benefits relating to EoL.

The most important improvement relating to manufacturing was re-design of the brewing groups. A solution already implemented in another coffee machine, Appia II, was employed in this case, which involved removal of the chromium plate in the lower part. This led to simplification of the assembly and a reduction in the quantity of material used. In addition, upon analyzing the geometry of the group it was noted that the height could be reduced without compromising the functionality and assemblability. A reduction of about 20% in the mass of brass was therefore achieved in the upper part (Fig. 4).

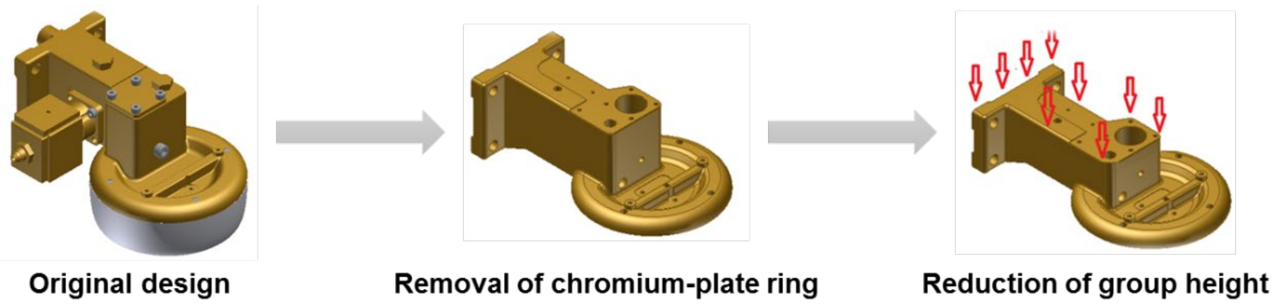

Fig. 4.Eco-design of the brewing group.

All of the implemented eco-design solutions allowed reduction of both the energy consumption and overall environmental impact related to the manufacturing and use phases. A summary of the obtained technical outcomes is reported in Table 7. These results demonstrate the effectiveness of the course in supporting companies with no prior eco-knowledge in improving their products.

Table 7. Main technical outcomes of the eco-design project.

Design solution	**Comparison with the original design (Italian intensive use scenario)**	
	Δ Manufacturing [kg CO_2eq]	**Δ Use [kg CO_2eq]**
Adoption of T3 technology (smaller main boiler, two secondary boilers, smaller resistance)	+4.7	-2098.1
Insulation of main and secondary boilers, brewing groups, pipes	+1.3	-1650.1
Re-design of the frame base	-7.7	Approx. 0
Re-design of the brewing groups	-10.7	Approx. 0

5.2. Teaching approach results

The proposed eco-design training course gave the company the opportunity to start a program oriented towards environmental sustainability and life cycle thinking. A simultaneous improvement in technical (e.g. coffee taste and quality) and environmental (e.g. energy efficiency and product recyclability) performance was achieved by developing design solutions aimed at product innovation.

Considering the proposed marking scheme reported in section 3.3 used to gather data from the assessment, the following results were observed (Table 8).

Table 8. Results of the assessment.

Type	**1st assessment**	**2nd assessment**
Average mark	2.2	4.1
Minimum single person mark	1.7	3.2
Maximum single person mark	3.7	4.6

The average mark upon completion of the first initial test was 2.2, while the average mark upon completion of the second final test was 4.1. The minimum mark obtained after completion of the first test was 1.7, while the minimum mark obtained upon completion of the second test was 3.2 (see Table 8).

A quantitative analysis of assessment results gives an overview of the main outcomes achieved through implementation of the training course within the company. Firstly, the average mark improvement (2.2 vs. 4.1) shows how awareness and knowledge of eco-design increase significantly upon completion of the course. It is worth noting that the general level of knowledge was low before the test, just above the "sufficient" mark (2.2). On the other hand, by observing the individuals involved in the training activity, the lowest value obtained after the course was 3.2. As such, all employees attained at least a "good" level of eco-design knowledge.

Answers gathered for the open-ended questions provided better insight into eco-knowledge transferability to the specific product. In particular, these questions were designed to understand how company products (i.e. professional espresso coffee machines and equipment) could be improved in terms of environmental performance. As per personnel responses, the three main eco-design actions (highlighted by 90% of respondents) for improving the environmental performance of the analyzed products were:

- energy efficiency and reduction in energy consumption for coffee brewing or boiling water;
- link between the material selection for product manufacturing and the product end-of-life strategy/scenario (adoption of closed-loop scenarios such as product retirement for refurbishment/remanufacturing);
- avoid the use of hazardous materials or rare earth materials (e.g. in electronic components).

These answers are in line with the main outcomes of the LCA analysis performed on the company product portfolio and the eco-design guidelines defined during interpretation of the results. In particular, the abovementioned actions allow a reduction in coffee machine life cycle carbon footprint of approximately 20% to be achieved and can be considered the most important eco-design actions for improving the environmental performance of these products.

Additional open-ended answers were also collected as specific eco-design actions for these products: (i) define a fast disassembly plan (with related documentation) for removal of the external chassis, (ii) redesign the electronic board to be smaller, with the minimum number of components possible, (iii) reduce the length of pipes from the main boiler to the brewing groups, (iv) develop solutions/technology that are strongly oriented towards the specific market (i.e. United States, Italy, etc.), and (v) create a reverse supply chain for product retirement (e.g. product loan for use). These answers fit with the personnel profiles involved in the training course and can be ascribed to the specific background of each single employee (e.g. management, marketing or engineering).

Based on the code used to cluster the open-ended answers (see section 3.3), it is worth noting that answers provided by participants concerning eco-design actions covered all lifecycle phases of the product under investigation, equally shared between the material and manufacturing, use and EoL phases. On the other hand, answers provided by the participants concerning environmental issues related to design choices were mainly focused on the use (40%) and EoL (45%) phases. Both clusters highlight how the eco-design teaching approach provides the right focus on environmental aspects in relation to the analyzed context of professional coffee machines and energy-related products.

6. Discussion

Analysis of the described outcomes leads to interesting insight into the advantages and disadvantages of the proposed teaching approach, which will be discussed in this section. The potential of the proposed approach is presented in section 6.1, describing how it can close the gap between existing barriers highlighted in the literature and implementation of eco-design within manufacturing companies. The main limitations of the eco-design teaching approach are instead discussed in section 6.2, including possible remedial actions to address these issues.

6.1. Progress against existing barriers

From analysis of the test results, it is possible to argue that there is a link between the main outcomes reported above and the barriers identified in the state-of-art concerning adoption of eco-design initiatives in the industrial world.

Firstly, development of the proposed eco-design training program via a structured partnership with environmental experts from academia was found to stimulate the company to become active in the field of environmental sustainability, stimulating a desire for specific eco-knowledge relating to their products. This aspect is demonstrated by the fact that the personnel involved attained a good level of knowledge (average value of 4 on a scale from 1 to 5) relating to eco-design practice. One of the most important results deriving from the test was increased employee awareness of the importance of considering the life cycle during product development. This is an important outcome considering the existing barrier of specific eco-design knowledge acquisition defined within the state-of-art and highlighted by several authors (Lindahl, 2006; Neri et al., 2018; Pinheiro et al., 2018). Based on responses to the test, all participants identified use of the product as the most critical phase in terms of environmental impact. Energy consumption and eco-design actions relating to reduction of energy consumption were seen as the most important initiatives in the development of new technologies for espresso coffee machines oriented towards environmental sustainability. Another relevant aspect concerns the importance of coffee machine end-of-life. In particular, the adoption of recyclable materials, in conjunction with technical solutions for ease of disassembly, were seen as an important improvement to achieving environmental sustainability. Moreover, participants from management and marketing understood how the product end-of-life could be an important resource to exploit for the development of new business models (e.g. remanufacturing and product service), reducing the ecological footprint of products while enlarging the company business market with a better brand image. This last aspect is fully compliant with one of the main drivers highlighted by the literature analysis (van Hemel and Cramer, 2002; Bey et al., 2013; Iranmanesh et al., 2018).

Secondly, this kind of teaching approach was found to be appropriate in a context where time and resources for environmental analysis were lacking. This aspect is in contrast with another barrier defined in the state-of-art which is the lack of allocated resources for environmental analysis (man power and time) (Le Pochat et al., 2007; Jabbour and de Sousa Jabbour, 2016). Based on the fact that the eco-design guidelines and knowledge were retrieved through analysis of the company product portfolio, environmental aspects were addressed in the standard product development process together with other design drivers (e.g. cost, functionality and performance), providing a framework for trade-off analysis. In addition, the time required for implementation of eco-design features upon completion of the proposed eco-design teaching approach was closer to “industry timing” or “time to market” than the time generally required to train employees on LCA using traditional approaches (e.g. lectures or refreshment courses from consultants).

Thirdly, in relation to lack of relevant/suitable methods and tools to support eco-design initiatives, the proposed approach provided a ready-to-use system that functioned as a framework for the development of new products or for the improvement of environmental features on existing products. On the contrary, the proposed framework was not a way to quantify environmental benefits relating to the developed design solutions, which is a shortfall of the proposed approach.

Lastly, the specific eco-design guidelines developed based on analysis of the company product portfolio allowed problems relating to a lack of information about alternative solutions with better environmental performance to be effectively dealt with. The eco-design guidelines helped with material, manufacturing processes and technology selection with a life cycle perspective.

6.2. Limitations of the eco-design teaching approach

The main point of eco-design teaching is to know if trainees can re-use the acquired knowledge on a new project. Further to bringing new knowledge to the company, the proposed training methodology consisted of accompanying internal domain experts with external environmental experts. In relation to the main limitations of the proposed eco-design teaching method, two main aspects must be considered:

- personnel were not “educated” in the use of a specific tool for the quantitative assessment of environmental performance;
- eco-innovation and development of new design concepts/technologies required the involvement of an external expert to assess the obtained benefits.

The current training course is organized to “educate” industrial engineers and practitioners on eco-design aspects without teaching them the basis of environmental sciences, which are commonly part of the background of environmental experts (consultants). To address this issue, a possible solution may be identification of a key figure within the company to be responsible for environmental issues. This “environmental manager” or “eco-design manager” would have the objective of bridging the gap between eco-innovation (eco-design actions) and quantitative assessment of the implemented actions. This figure should also be involved in the training course, filling in missing competences within the company. The required background of this manager should be related to environmental sciences and life cycle engineering. For small and medium enterprise (SMEs), however, such a figure may not be present due to limited resources. For this reason, an internal employee with a technical background could be trained on life cycle sciences through a specific course developed alongside the proposed eco-design teaching approach. In this scenario, the teaching eco-design approach could be structured according to two complimentary levels: (i) a basic module (eco-design) for all identified key personnel, and (ii) an advanced module focused on life cycle assessment and environmental assessment for the future environmental manager.

Considering a different context, where the involvement of an external eco-design manager is required due to the complexity and variability of a product portfolio, different strategies can be adopted for re-use of eco-knowledge and guidelines for development of a new project. A possible solution would be the creation of a structured eco-knowledge database (DB), internal to the company, which could be easily accessed and upgraded (Germani et al., 2013; Rossi et al., 2013). This repository should be developed with the aim of containing material related to product environmental sustainability for the following functions:

1. to provide tangible support for engineers/designers early in the design process. This function is supported by consultation with technical documents organized in a clear and structured manner such as: (i) training material, (ii) specific and generic eco-design guidelines, and (iii) additional and supplementary materials;

2. to stimulate the customization of eco-knowledge and creation of new knowledge related to eco-design. This function is supported by definition of the following attributes for each guideline: (i) an eco-design score able to establish guideline priorities, and (ii) an applicability index level for evaluation of guidelines accordingly to a company's specific area;
3. to support knowledge sharing among actors involved in product design thanks to thematic organization of material and support in defining and verifying milestones.

Considering the proposed scenarios, the company may become self-governing in the development of more sustainable products from an environmental perspective. In particular, the company can autonomously compare design solutions with the aim of assessing benefits introduced by eco-innovations. The adoption of the proposed approach will also contribute to enriching the in-house level of eco-knowledge and company awareness of this subject.

7. Conclusions

The present paper describes how a novel teaching approach for eco-design can be implemented within a manufacturing company with the aim of training employees involved in product development. Collaboration between academia (environmental experts) and a manufacturing firm (company employees) allowed the gap between the use of standardized methods (e.g. LCA) and useful guidelines for eco-design in the field of energy-related products such as espresso coffee machines to be closed. The life cycle analysis of a company's product portfolio requires involvement of the company's employees, firstly to retrieve useful data for life cycle inventory, and secondly to analyze the outcomes of lifecycle analysis through the development of eco-design guidelines. The training course allows an important level of eco-knowledge to be attained within the company, which can be shared in technical departments during future product development focused on both new and existing products. This is an important advantage considering the possibility of re-using the acquired eco-knowledge for development of new projects and products.

The proposed model (teaching approach) can easily be reproduced in different contexts considering the specific requirements and objectives. The presented case study shows how the eco-design teaching approach was implemented in a real context, with relevant improvements in terms of the level of eco-knowledge gained by the trained personnel. Through assessment, an average "very good" level of eco-knowledge relating to products developed by the company was obtained after implementation of the course. This is an important achievement considering that before the course the average level of eco-knowledge was barely "sufficient". Another important advantage of the proposed method is related to learning outcomes that are not focused on a specific tool for environmental assessment (e.g. LCA), but rather derive from the assessment of a company's product portfolio used to drive eco-design actions.

In relation to drawbacks, environmental benefits gained from the adoption of eco-design actions cannot be directly assessed and still require the involvement of environmental experts (LCA practitioners). The involvement of an environmental manger within the company, however, could close the gap between the required level of expertise in environmental sciences and the desired level of eco-knowledge required by employees. Thus, technical and environmental competences could be coupled to develop more sustainable products.

This case study was the first attempt at implementing the training method within the design departments of a manufacturing company, and was carried out by considering a limited number of people (i.e. eleven employees of the involved Italian company). A more statistically significant sample, as well as more trials are required to fully validate the proposed teaching approach and thoroughly understand its advantages and limitations. This aspect represents the most important future research for further development and testing of the approach with different products and within different contexts.

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Appendix A

Closed-ended questions #	Question	Answer
1	What implies Life Cycle thinking for an ErP product (e.g. a professional espresso coffee machine)?	a) Consecutive and interlinked stages of a product or service system, from the extraction of natural resources to final disposal
		b) That everyone in the whole chain of a product's life cycle, from cradle to grave, has a responsibility and a role to play, taking into account all relevant external effects related to the product
		c) Defining a functional unit can be quite difficult, as the performance of products is not always easy to describe
		d) None of the above
2	What is a lifecycle analysis?	a) A way of figuring out the overall impact that a particular human activity or a product has on the environment over its entire life cycle
		b) A way of figuring out the impact that a particular human activity or a product has on the environment while it is being used by the consumer
		c) A way of figuring out what impact a human activity or a product had on the environment while being manufactured
		d) None of the above
3	Which life cycle phases characterize an ErP product (e.g. professional espresso coffee machine)?	a) Raw material extraction, Manufacturing, Transportation, Product use, End-of-life
		b) Raw materials extraction and Manufacturing
		c) Product use
		d) Product use and End-of-life
4	Which "standardized" methodology and tool allows life cycle analysis to be performed for subsequent implementation of eco-design strategies?	a) PLM - Product Life Cycle Management
		b) LCA - Life Cycle Assessment
		c) CAD - Computer Aided Design
		d) CAE - Computer Aided Engineering
5	Why is the end-of-life phase considered a critical phase to model and manage an ErP product (e.g. professional espresso coffee machine)?	a) Because it is the final phase of the design process where all details must be defined and several people need to be involved
		b) Because it is the final phase of the overall product life cycle, which is very far from the design stage, and is affected by uncertainty
		c) Because it is the most impactful phase in terms of costs

		d) Because it is the most impactful phase in terms of environmental impacts
6	Is GWP (Global Warming Potential) the only environmental indicator used for life cycle analysis?	a) Yes
		b) No
7	From which documents can primary data for life cycle inventory related to the raw materials of an ErP product be retrieved (e.g. professional espresso coffee machine)?	a) Product CAD models
		b) Product Bill of Materials (BoM)
		c) Measurement campaign and dedicated interviews
		d) All of the above
8	Is it possible to use non-compliant RoHS materials in component manufacturing of an ErP product (e.g. professional espresso coffee machine)?	a) Yes
		b) No
9	Limited to the raw materials life cycle phase, is it preferable to use steel-based materials or aluminum alloys?	a) Steel-based materials
		b) Aluminum alloys
		c) Steel-based material and Aluminum alloys have the same environmental impact
10	Among the possible choices, what is the best eco-design practice to adopt for arrangement of electronic components in an ErP product (e.g. professional espresso coffee machine)?	a) Inside the product to avoid contamination from the external environment
		b) As far as possible from any possible heating source
		c) In the external part of the product to increase its accessibility
		d) Near the control panel to reduce the length of electrical connection
11	Limited to the manufacturing life cycle phase, is the selection of different manufacturing technologies (e.g. machining, stamping, sheet metal drawing) a critical aspect to consider for material selection?	a) Yes
		b) No
12	In a whole life cycle, how much is the share of GWP for the use phase of a professional espresso coffee machine?	a) more than 90%
		b) more than 50% but less than 60%
		c) more than 20% but less than 30%
		d) negligible
13	Is the GWP a "good" indicator for environmental characterization of an ErP product (e.g. professional espresso coffee machine)?	a) Yes
		b) No
14	Among the possible choices, what is the phase with highest energy consumption of a professional espresso coffee machine?	a) Warm-up
		b) 1 Espresso brewing
		c) 1 Flat-white preparation
		d) 1 Boiling water for tea

		e) 1 min Stand-by
15	Does a correlation exist between the use profile and environmental impact (GWP) of a professional espresso coffee machine?	a) Yes
		b) Yes, only for some preparations (e.g. espresso)
		c) No
16	Does a correlation exist between the country and environmental impact (GWP) of a professional espresso coffee machine?	a) Yes
		b) Yes, only for far-east countries
		c) No
17	Sort, from the most to the least sustainable, the following closed-loop end-of-life strategies	a) Recycling, Reusing, Remanufacturing
		b) Reusing, Remanufacturing, Recycling
		c) Remanufacturing, Recycling, Reusing
		d) All of them have the same environmental impact
18	Among the possible choices, which components can be designed for remanufacturing?	a) Brackets
		b) Aesthetic components
		c) Boiler and pumps
		d) None of the above
19	Among the possible choices, which eco-design solutions can be adopted to favor the disassembly of aesthetic parts?	a) Screws
		b) Rivets
		c) Glue
		d) Snap-fits
20	Between plastics and aluminum alloys, which material is more sustainable from an environmental perspective considering a recycling end-of-life strategy	a) Plastics
		b) Aluminum alloys
		c) Both of them have the same environmental impact
Open-ended questions Question	**Question**	**Answer**
21	Illustrate life cycle design actions that can be implemented for re-design of a professional espresso coffee machine	
22	Illustrate environmental concerns related to material selection of aesthetic components considering: (i)	

	plastics, (ii) aluminum alloys, and (iii) steel-based materials	
23	Illustrate some eco-design examples aimed at reducing energy consumption and related environmental impact (e.g. GWP) during the use phase of a professional espresso coffee machine	
24	Illustrate environmental and economic concerns relating to different closed loop end-of-life strategies (e.g. remanufacturing, product as a service)	