

Article

Using Product Design Strategies to Implement Circular Economy: Differences between Students and Professional Designers

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Abstract: Different studies in the scientific literature have shown how the transition towards a circular economy (CE) can benefit from product design, although maintaining a rather broad and qualitative perspective of analysis. This study investigates and compares which product design strategies (from routinely design, structural optimization, industrial design and systematic innovation) are most used by students and professional designers to implement different CE strategies (i.e., waste reduction, reuse, remanufacturing, recycling and biodegradability). Students' data were collected from year projects and MSc degree theses based on real industrial case studies and carried out in two Italian engineering universities, while those of professional designers, were collected from selected scientific articles. Among the main outcomes emerged that the design strategies deriving from systematic innovation were preferred by students quite clearly. The design strategies referred to industrial design, e.g., user-centered design and timeless design were preferred by professional designers. The design strategies related to routine design, i.e., materials substitution, reducing resources and energy consumption, and structural optimization, were indistinctly used by both students and professional designers. The obtained results and their discussion can be useful during eco-design teaching to show the main gaps that students should fill in comparison with professional designers.

Keywords: eco-design; teaching; design strategies; TRIZ; circular economy; circular economy strategies

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1. Introduction

The transition from linear to circular economy is complex and can benefit from a vast amount of supporting theoretical and practical approaches (e.g., [1]). Among them there are also the design strategies for intervening on the product, on which the circular economy is to be implemented.

In the literature, the “design strategy” label is typically used as an umbrella term to include different and heterogeneous approaches for intervening on a product. In relation to the modifications provided to the product, the design strategies can be classified in different ways, e.g., based on the type of the suggested design intervention, i.e., innovation vs. optimization (e.g., [2]), to the extent of the intervention, i.e., marginal on a few components or extended to the entire product, and to the considered design entities, e.g., product function, behavior and structure (e.g., [3]).

The application of the design strategies to favor the transition to the CE of a product, consists of redesigning the product itself. According to the supporters of this position, product redesign in this perspective is necessary when the application of one of the CE strategies (e.g., waste reduction, product reuse, product remanufacturing, materials recycle) can be easily, safely and cost-effectively implemented on the entire product or on some of its components [4].

The use of the design strategies is not the only option for implementing the CE. The intervention on other aspects, such as product logistics, or user education can, in fact, be as beneficial for the CE. Their combination with product design can sometimes be obliged and in general can lead to greater benefits for environmental sustainability (e.g., [5,6]).

However, the application of the design strategies is not a trivial process, regardless of the objective of applying them to implement the CE. Their understanding and effective application require a lot of time and experience and cannot be separated from an adequate training. In this perspective, the understanding of the students' limitations and problems in facing a design activity, compared to professional designers, can be crucial (e.g., [7]). The same considerations apply to several researchers even when the objective of applying the design strategies is to facilitate the transition to the CE (e.g., [8]).

In the literature, the study of how design strategies can support CE has been duly addressed (see Section 2). However, at least three main limitations emerge from the analysis of the various contributions to the state of the art. (1) The analysis was carried out only in too specific application areas, consequently the obtained results do not have general validity. (2) Due to the too high level of detail of the analysis, it is not clear which design strategies can best support the CE and according to which of its strategies (e.g., recycle, reuse, etc.). (3) The problems that students may encounter when applying design strategies to support CE do not explicitly emerge.

To overcome these limitations, this study proposes an analysis of which design strategies are most used to support the transition to the CE, comparing the choices of engineering students and professional designers. The findings of this study were obtained in two different ways. Those of the students in an empirical way, analyzing the results proposed in end-of-course projects and MSc degree theses in mechanical or management engineering in two Italian universities, i.e., University of Bergamo and Marche Polytechnic University. While those of the professional designers analyzing instead selected scientific articles and work experiences.

Compared to the contributions to the state of the art, the novelty of this study can be found in three main points:

1. The analysis is based on many case studies related to different application domains, in order to consider more heterogeneous design strategies and obtain results with a general validity.
2. The comparison between the design strategies and the CE strategies was performed at a finer level of detail to make the reader aware about which design strategies was used and for what purpose.
3. Different results were obtained both by professional designers and students and they were compared to understand their different perspectives, due to experience and to identify the main gaps of the students in comparison with the professional designers.

Furthermore, the students and the professional designers have a similar school preparation, but a different practical experience, since almost all the professional designers considered have been working in the company for several years. Thus, this study can also investigate the effect of work experience.

The results obtained from this study may be useful to different subjects involved in design and circular economy, for different purposes. A student could understand which areas of design to focus more on and what kind of knowledge to deepen. An engineering design teacher could understand instead which are the gaps of the students on which it might be more appropriate to insist when teaching design and eco-design. In addition, a teacher could also investigate whether some aspects deriving from less rigid and more creative approaches in dealing with design, such as those deriving from industrial design, could be integrated into engineering courses. On the other hand, a professional designer might explore the possible differences with an engineer having a different background, albeit with less experience, in approaching design to accomplish the same goals.

This paper is structured as follows. Section 2 illustrates a state of the art about the studies that have already tried to identify which design strategies might be more suitable for supporting the transition to the CE. Section 3 presents in detail which design and CE strategies were tested and compared in this study and the testing methodology, describing the test participants, the considered case studies, the modalities of executions of the tests and those of their analysis. Sections 4 and 5 present and discuss the obtained results. Finally, Section 6 draws the conclusions.

2. State of the Art

2.1. Overview about the Design Strategies

In the literature, design strategies of different types were proposed. At a macro-level, some design strategies support the designer through a more traditional approach, mainly aimed at structural optimization and based on small incremental changes, while others suggest more radical changes to the product, questioning its conceptual idea.

Typically, the first ones involve the mass reduction and the replacement of materials and components. While the second ones can instead stimulate to rethinking the design entities, e.g., Function, Product Behavior (e.g., Function-Behavior-Structure-FBS-theory [3]), to user-product interaction (e.g., [9]), and to a greater and more rational exploitation of the resources (e.g., TRIZ [10]).

Moreover, different design strategies suggest profoundly different ways of approaching a design activity. In structural optimization, the design strategies first support a functional, kinematic or dynamic analysis of the product structure and then the refinement of the same structure. While, in product innovation, the design strategies push the designer to immediately abandon the more concrete level of structural aspects and to work on a more abstract level, where the requirements, function and behavior of the product are re-discussed. Then, the strategies therefore suggest seeking abstract solutions to the initial problem, also reformulated in an abstract way and, at the end, to contextualize in line with the initial domain.

2.2. Applying the Design Strategies for the CE

Convinced that product design could support the transition to CE, some authors have therefore questioned which design strategies were most suitable for this purpose, comparing different ones within systematic reviews. However, although these contributions succeed in providing a general overview of the topic, at least three limitations, evident to any researcher analyzing the reference literature, must be overcome in order to ensure reliability to the obtained considerations.

In several studies, the considered application field concerns specific sectors, such as buildings construction (e.g., [11]) or fashion (e.g., [12]). While in other studies, only a certain area of design is considered, such as biomimicry (e.g., [13]) or user-centered design (e.g., [14]). In both cases, the resulting analysis is limited to only a few design strategies, typically applied in a restricted field and/or referred to the given design domain. Furthermore, this narrowness in the considered domain can also limit the number of considered CE strategies.

Another limitation present in some studies concerns their ability to suggest which design strategies can support CE and how. Some authors analyze only a few design strategies (e.g., [15]), reducing the number of possible comparisons. While others analyze the design strategies at a too high level of detail, considering the classes of design methods rather than to the single strategies [16,17] or explaining only the context information of a design activity or of a design framework that are more suitable for the CE (e.g., [18]). In both of these two cases it is not clear how a design strategy can actually be applied to support the CE.

Finally, the literature does not provide an analysis specifically dedicated to students' problems and their limitations in applying the design strategies to favor the transition to

the CE. Some studies describe only the typical problems of professional designers (e.g., [11,19]). Others propose instead generic considerations, having general validity for both professional designers and students (e.g., [14]).

On the reasons why, the teaching of CE concepts is only spreading in recent times, deepening only marginally on some aspects such as the role of design, several explanations from the literature were collected by [8]. According to the authors, theoretical knowledge is still too new and undeveloped in industrial practice. CE-based product development is even more recent and industrially applied only in a marginal way. The first regulations about CE practice have been adopted by the states only in the last five years. Teachings about CE described in the literature are few and too heterogeneous to provide an accepted reference. However, according to the same authors, teachers should not be discouraged from teaching the circular economy. On the contrary, due to the promising results presented in the literature about some experimental courses about CE and increasing industrial interest, CE teaching will spread rapidly in the coming years.

In conclusion, despite the best predictions for the future, at present the gaps between students and professional designers has not yet been studied in the literature.

3. Materials and Methods

In this section, the definitions of the tested design strategies and CE strategies are presented in detail, after having specified the criteria underlying their selection.

3.1. Tested Design Strategies and CE Strategies

The tested design strategies were selected from the scientific literature in order to provide a broad overview of all the main approaches to design, both the more traditional ones, based on structural optimization, and the more innovative ones [20]. Although the considered design strategies have general validity, some studies have also applied them in the field of eco-design and, sometimes, with the aim of favouring the CE (e.g., [21,22]). Furthermore, their effectiveness in reducing the environmental impacts has been positively estimated, both from a qualitative (e.g., [23,24]) and quantitatively point of view (e.g., [25]).

In the following paragraphs, the tested design strategies are presented and described in detail.

1. “Substituting the product materials” consists of replacing the constituent materials of the product components with others having better characteristics for different aspects. Longer material life can reduce the waste and premature replacement of components. The lower mass of the material, conserving the mechanical resistance, is instead useful for reducing the energy consumption required to handle the product during the operating life and the transportation. The lower environmental impacts of the material during extraction, processing and disposal, allow instead to increase the environmental sustainability of the product.
2. “Substituting the energy source/technology” consists of replacing the power sources of the product and/or the technologies on which they are based, by privileging the most efficient and least impacting ones.
3. “Optimizing the product structure” consists of reducing the mass of the product by conserving its features (e.g., structural strength) and without replacing the constituent materials. In this way, by reducing the amount of material, environmental impacts are also reduced during extraction, use, and transport.
4. “Designing the product considering the user experience” consists of a change in the designer’s perspective when designing a product to favour its usability. For this reason, the focus during the initial parts of the design activity is shifted from the structure of the product to the mode of user interaction, depending on the context of use, ergonomics, affective dimension and cognitive experience [9].

5. “Dematerializing the product components” consists in eliminating and replacing them with another entity able to perform the same function. In the case of Trimming, as typically explained by TRIZ [26], the removed component is replaced by another component of the product that is used as such, if possible, or is modified accordingly. Another possibility, always suggested by TRIZ, is the Dematerialization, which can be declined in three different ways. According to TRIZ Evolutionary Law N. 7, the component to be eliminated is miniaturized, but not completely eliminated, by making it thinner or breaking it down into many small parts until it becomes dust, e.g., by passing from a saw to a diamond cutting disk. According to the same law, a phase transition of the component from solid to fluid state can also be considered, e.g., replacing a saw with the waterjet cutting. Finally, according to TRIZ Evolutionary Law N. 8, the component is eliminated completely, replacing it with a mechanical, chemical, fluid-dynamic, acoustic, electrical, magnetic, or electromagnetic field, e.g., substituting a saw with the laser cutting.
6. “Segmenting/dynamizing the product parts and rhythms” consists of designing a product in such a way that it can better adapt to the characteristics of the operative context and the other entities. This strategy summarizes the essence of different approaches exploited by the TRIZ method to innovate a product. At a structural level, the different parts of the product can be disrupted and recombined in a more appropriate way, also allowing them a possible reciprocal mobility to increase their flexibility (TRIZ Inventive Principle N. 1) or by improving their quality locally, only where it is actually needed (TRIZ Inventive Principle N. 2). The product’s mode of operation can also be improved by dynamically adjusting work rhythms in relation to actual function and environmental needs (TRIZ Inventive Principle N. 15).
7. “Exploiting modularity/using standard parts” consists of redesigning the product by exploiting components more standard and easily to be substituted and that are common or shared with other products. In this way, production costs can be reduced, avoiding the creation of ad hoc components and facilitating the maintenance and production of product components, also standardizing the manufacturing procedures to make them more environmentally sustainable [27].
8. “Exploiting the resources/Recovering the energy” consists of identifying and using any means, both in the working environment and within the product, to reduce the consumption of raw materials, auxiliary materials and energy, related costs and environmental impacts. This is provided that systems are introduced for their exploitation that do not compromise the obtained benefits [18]. The definition of “resource” provided by the TRIZ method is one of the broadest, including also physical effects that are commonly considered as harmful, e.g., vibrations, but that can be useful if specifically exploited. A resource can be a physical entity to be used as is, or geometric, i.e., a morphological or a surface feature of the object (e.g., inclined plane, roughness) or even just an empty space to be exploited. The waste energy to be reused can be in any form, e.g., kinetic or thermal, including latent state energy, such as heat from the phase transition of a material (TRIZ Inventive Principle N. 36).
9. “Providing a timeless design to the product” has the objective of prolonging the operating life of the product, ensuring that the user does not discard it prematurely. A typical way to achieve this is to improve the design of the product, while considering how user’s needs might change over time, to make the product attractive to other users for reuse to perform the same or another function.

The tested CE strategies were selected to provide a comprehensive overview of all the different ways in which CE can be implemented. To identify the CE strategies, an accurate analysis of the scientific literature was carried out by the authors. Among the various contributions selected, the reviews of [28,29] were taken as a reference for their completeness and accuracy in providing, classifying and analysing the main CE strategies. The CE strategies tested in this study were selected among them. The criteria for the selection are the completeness in referring to the different phases of the product life cycle

and considering the many related aspects as prescribed by international regulations for eco-assessment (e.g., ISO 14040 and ISO 14044). In addition, the CE strategies were also selected because each of them refers to one of the main alternative options to implement CE (see Figure 1) and they are completely alternative. In this way, the goal is to minimize the intersections between the tested CE strategies and therefore to avoid possible misunderstandings.

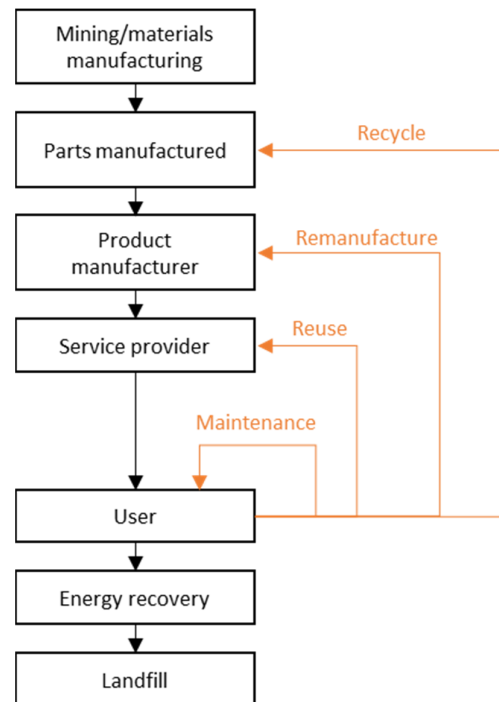


Figure 1. Example of subdivision scheme of CE options

In the following, the tested CE strategies are presented and described in detail.

1. “Reducing the waste” is intended to decrease the environmental impacts associated with waste and, at the same time, those resulting from the production of new products or replacement components. Increasing product service life, structural optimization aimed at reducing the mass of product components (e.g., [30]), fluid dynamic optimization aimed at rationalizing fluid auxiliary materials (e.g., [31]) and the dematerialization of the structures obtained by introducing fields (e.g., [10]) are just a few of the declinations that have been associated with this CE strategy in the literature.
2. “Reusing the product” allows to extend the product operational life by identifying new uses for it beyond that for which it was designed, when this latter is compromised due to the product’s inability to perform the main useful function or meet secondary requirements. The main requirement behind this strategy is that the product must not undergo any processing prior to its reuse. The main declinations of this strategy, which can be learned from the literature, suggest to make the product structure more durable (e.g., [32]) or more easily modified to be readjusted for future needs (e.g., [33]).
3. “Repairing/Refurbishing/Remanufacturing the product” allow the product, once compromised, to be reused for its original use or a new one, provided it is restored to its original state or one compatible with the new requirements, after restoring it to its original state, by ensuring the new requirements. From the environmental perspective, this strategy pays if the impacts from product restoration operations are offset by the reduction in impacts achieved by not disposing of the product [34]. The

prerequisite for the application of this strategy depends on the ability to intervene in the product structure to restore its functionalities, which in turn depends on both the organization of these operations and the structure of the product itself [35].

4. "Recycling the materials of the product" allows the materials of the product to be reintroduced into its life cycle or into that of other compatible products, thus avoiding the phase of extracting new virgin materials. This strategy can be declined in two different ways depending on the flow of recycled materials [36]. In the case of ecosystem restoration, the objective is to regenerate the biological cycles of various ecosystems including forests, fresh water, and inland wetlands, through different processes including extraction of biochemical feedstock, farming, and anaerobic digestion. While, in the case of technical recycling, the objective is instead to regenerate the technical cycles, or to reproduce the constituent materials of the product components, such as for recycled paper and plastic.
5. "Making the product biodegradable" has the objective to improve the product so that its disposal has less impact, using biodegradable materials that decompose more quickly, emitting fewer pollutants and requiring fewer resources [18]. In the literature, this strategy typically refers to the use of natural materials, both the completely natural or the bio-based ones, used in place of, or in combination with, synthetic materials [37]. The main environmental benefit of this strategy is found in the reduction of the amount of waste that must be disposed of in landfills or in incinerators.

3.2. Testing Methodology

In order to study which design strategies were most considered by students and professional designers to facilitate the transition towards the CE, and in particular towards which CE strategies, two different rigorous procedures were followed. In the case of students, the solutions proposed during year projects and MSc theses were collected and analyzed by the authors, integrating them with the answers to some interviews with students on the most interesting and difficult to understand aspects. The solutions proposed by professional designers were collected from articles published in peer-review international journals.

This choice was made for two reasons. On the one hand, the availability of the solutions played a fundamental role. In the case of students, the authors were able to collect dozens of works over seven years. In addition, all these students were supervised by the same authors. In this way, the authors were able to control how students carry out their work, without influencing them in any way. On the other hand, a comparable number of solutions provided by professional designers was not available. For this reason, the choice to consider the contributions from the literature relating to the work of professional designers is also a way to ensure greater reliability in the comparison carried out in this study. Differently to the students, the geographical domain from which the data of professional designers were collected is wider, being of an international scale. At the same time, the modalities to collect the results of the professional designers can be considered reliable and rigorous, based on the statements provide by the authors in the considered articles and the rigorous peer-review process to which these latter have undergone.

In the following sections, the two procedures that were followed to collect and analyze the solutions from students and professional designers are described.

3.2.1. Testing Methodology for Students' Solutions

All the students (39, 11 females and 28 males) were studying toward an MSc in Mechanical Engineering (22) or in Management Engineering (17) at the University of Bergamo or the Marche Polytechnic University. Six of them proposed the solutions during their MSc thesis, while 33 proposed them during the year projects of two University courses, named Methods and Tools for the Product Life Cycle (i.e., PLM), common to both

curricula, and Product and Process Innovation, dedicated to mechanical engineering students. Both the courses, during 60 h of lectures, teach the fundamental principles of eco-design, eco-assessment, product lifecycle management (i.e., PLM), engineering design and systematic innovation (mainly through the TRIZ method). All the students who completed the thesis also followed one of these two courses.

The Testing Technique for students' decisions about the selection and the use of the Design strategies and CE strategies to solve the assigned problems is the following.

Before taking the test, the students were instructed in product design and environmental sustainability within the two mentioned university courses in which some supporting methods and tools were also presented.

During the test (final project or thesis) a problem to solve was assigned to each student. This problem is a real industrial case study about a product to be made more environmentally sustainable. The students solved their problem autonomously. The average full-time workload of a final project can be quantified in about two weeks, while that of a thesis is over a month, considering only the application phase of the design strategies and the determination of the solutions. In carrying out the year project, students could draw on any source of technical and theoretical knowledge. The theoretical preparation and the supporting material, used by the students during the development of the final project or thesis, was mainly provided through the two university courses previously mentioned. In addition, the students were encouraged to draw further knowledge from their entire university experience. The students were asked to present the solutions in a rigorous and complete manner, by providing all the details of the structural aspects and the functioning. Furthermore, the students were also asked to specify, according to their perception, how their solutions could implement the CE concepts.

The solutions proposed by the students were carefully analysed by the authors who determined which Design strategies and which CE strategies (among those presented in Section 3.1) were exploited by the students.

The case studies that the students worked on, determining the solutions analyzed in this study, are described in the following paragraphs.

A compressed air dryer, of the adsorption type with hot regeneration, is a device used to remove moisture from a continuous flow of compressed air stream, produced by an industrial compressor and used in an industrial plant. The application field is typically in oil and gas plants or downstream of a compressor feeding an industrial plant. The elimination of the moisture from the plant is necessary in order not to cause corrosion damage to machinery and tools connected to it. Its operating principle is based on the chemical process of adsorption, in which the water vapor present in the compressed air is chemically bound to an adsorbent material, i.e., activated alumina. This product consists of two tanks containing the desiccant material, typically alumina. The flow of wet compressed air passes through one of the two tanks and the alumina removes the moisture from it by adsorption. Meanwhile, the other tank is heated by a stream of air to regenerate the alumina that has absorbed moisture, evaporating the latter. Then, the system reverses its mode of operation. A system of automatic piping and valves regulates the flows of compressed air and hot air between the two tanks. The alumina is regenerated because it loses some of its adsorptive effectiveness after each regeneration cycle and for this reason it is replaced every two years. With reference to the energy consumption, this product is positioned in the high efficiency range. The main constituent materials are painted carbon steel for the structure, and stainless steel for the alumina tanks and most of the pipes. The main inefficiency of this product is the energy consumption to regenerate the alumina.

A front-loading domestic dishwasher consists of an airtight cabinet, inside of which dirty dishes are stored, by disposing them vertically in a dedicated basket. Above and below the plates, two counter-rotating arms that spray water through several nozzles, directing it toward the dishes. The considered model is one of the most widespread on the

European market and is produced in Italy. The reference energy class of the dishwasher is “A+”, according to European Union energy label. The most used materials are stainless steel sheets for the frame and internal components and the glass for the front frame. The main inefficiency of this system is the consumption of hot water since it is sprayed in excess, even against the walls in order to exactly wet all the dishes. The problem is geometric since the basket is square, while the two rotating arms describe two circular orbits, inscribed in the perimeter of the basket.

A pelletizer is an industrial machine dedicated to the automatic production of pellets starting from wood chips obtained from industrial and agricultural waste and compressing it mechanically without adding additives. The obtained pellets, with a density of 650 kg/m³, a humidity of less than 11% and an energy value of about 4.8 kWh/kg (against the 10 kWh/L of diesel and the 9.8 kWh/m³ of natural gas), are typically used as fuel for domestic heating. The pelletizer consists of several parts. An extruder produces the pellets starting from the raw material, by means of the action of a pusher driven by compressed air that is produced by an electric compressor included in the machine. A steel tank, located upstream of the extruder, contains the raw material, which is sent to the extruder via a sloping steel connecting duct exploiting the gravity. Finally, a steel frame contains all the parts, including the control part with which the user interacts.

A glass bottle for water, soft drinks or wine needs to be redesigned in order to reduce its environmental impacts throughout its life cycle. For this case study, no particular constraints were set about the shape and type of material, other than compatibility with its content and the useful volume. The production method is the standard one. The bottle is obtained by melting a homogeneous mixture of minerals and glass waste in an oven at a high temperature (about 1500 °C). The molten glass comes out of the oven and is fed into the molds for forming and cooling. In this phase, the surface of the bottle undergoes sudden changes in temperature which also give it its mechanical strength. Glass recycling recovers a high rate of raw materials.

An Electric oven, referring to the most popular on the European market, includes a bottom and top electric resistance and an electric thermostat to control their operation. The oven is heated thanks to the use of electric coils that heat up due to the joule effect and transmit heat to the dishes by convection and radiation. The considered model is one of the most widespread on the European market and is produced in Italy. The internal volume of the oven is 68 L. The reference energy class of this appliance is “A+” both for the cooking and the hood, according to European Union energy label. The most used materials are stainless steel sheets and glass on the front frame of the oven. The main inefficiencies of the product occur during the use of the oven due to the excessive energy consumption of the electric coils.

Figure 2 shows the products of the case studies that students addressed in their final projects and theses.

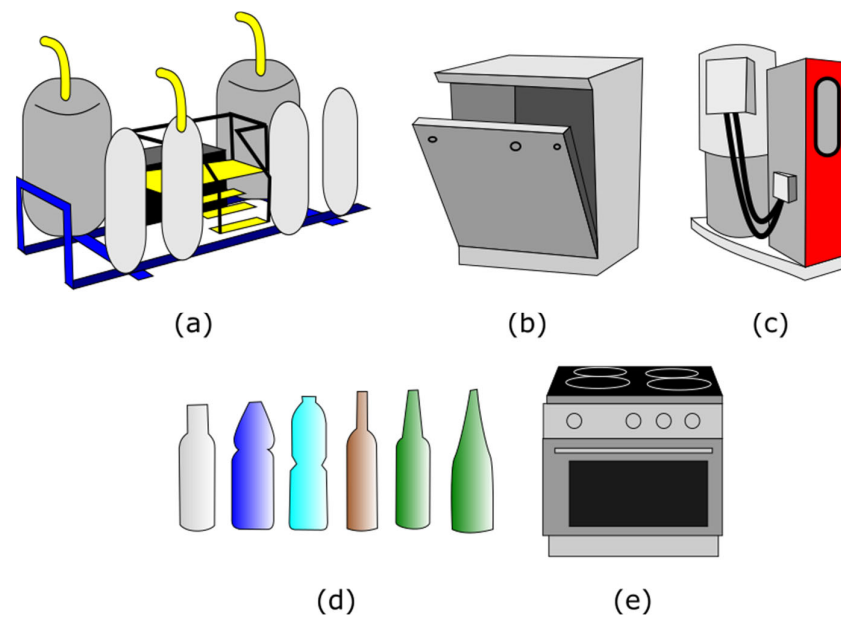


Figure 2. The case studies which the students worked on: (a) Compressed air dryer, (b) Front-loading domestic dishwasher, (c) Pelletizer, (d) Glass bottle for water, soft drinks or wine, (e) Electric oven.

The solutions provided by the students were evaluated by the authors following a systematic step-divided procedure. The steps of the adopted procedure are described in the following paragraphs:

1. Firstly, the solutions were selected on the basis of their presentation criteria. Only those explaining in detail, with written descriptions and drawings, the following aspects, have been selected: structural and material arrangements, operating principle, design interventions carried out and advantages on environmental sustainability that the solutions aim to pursue, by specifying how CE can be implemented. Overall, the selected solutions are 183. All of them were evaluated by the authors.
2. The descriptions of the selected solutions were compared by the authors by analogy with the tested design strategies. To do this, the authors compared the lexicon used by the students with the definitions of the ontological terms with which the Design strategies are expressed, which in turn derive from the TRIZ method.
3. Then the authors also compared the descriptions of the solutions provided by the students with the CE strategies, always by analogy. In this case, the terms used by the students to describe their intentions in implementing CE were compared with the definitions of the terms used to define the CE strategies in Section 3.1, which derive from the reference literature.
4. To dispel the doubts of interpretation about the meaning attributed by the students to some terms within the descriptions, the same students were interviewed by the authors.

3.2.2. Testing Methodology for Professional Designers' Solutions

According to what is specifically stated in the considered articles, all the professional designers received an education comparable to that of the students, obtaining a degree in mechanical, industrial, or at least civil, engineering. While the level of experience of the professional designer is considerably higher than that of the students, both in design and in eco-design. The solutions proposed by the professional designers, which have been analyzed in this study, were obtained from 31 scientific articles collected from peer-review international journals. This choice was made to ensure greater reliability to the study.

Their research was made in Scopus and Google Scholar, by using the keywords “design” AND “circular economy” as query in their title and abstract.

The solutions from the articles were evaluated by the same authors by following a systematic step-divided procedure. The steps of the adopted procedure are described in the following paragraphs:

1. Firstly, the solutions were selected, keeping only those that have a detailed description according to the criteria specified in step 1 of the procedure adopted in the selection of the solutions proposed by the students (see Section 3.2.1). As a result, 93 solutions were collected from professional designers.
2. The descriptions of the selected solutions, provided in the selected articles, were compared by analogy by the authors with the tested Design strategies, in the same way as previously done to analyse students’ solutions (see step 2 of Section 3.2.1).
3. Moreover, this step was carried out in the analogous manner of step 3 of Section 3.2.1 to comprehend what CE strategies were implemented.

Step 4 (interviews to the authors of the solutions) was not possible in this case. For this reason, the authors could only analyse the written descriptions of the solutions in the selected articles, although their quality level is considerably better than those provided by the students.

The case studies described in the selected articles refer to different application fields. In Table 1, the references of all the considered articles are provided and classified according to the application field of their case studies.

Table 1. Classification of the considered articles in relation to their application fields.

Application Fields	Sources
Product industrial design	[6,16,19,38–49]
Buildings	[11,50–53]
Manufacturing, Additive manufacturing	[54–56]
Electronic and appliances	[57,58]
User behavior and user experience design	[14,59]
Fashion design	[60,61]
Medical	[62]

4. Results

In this section, the results obtained from the test for both students and professional designers are presented, compared and discussed. The methods for their presentation were chosen in such a way as to show the comparison between the use of design strategies and that of the CE strategies and highlight the differences between students and professional designers.

Figure 3 reports the total number of solutions proposed by the students for each intersection between a design strategy (please see the rows) and a CE strategy (please see the columns).

CE strategies \ Design strategies	1. Reducing the wastes	2. Reusing the product	3. Repairing / Refurbishing / Remanufacturing the product	4. Recycling the materials of the product	5. Making the product biodegradable	Total
1. Substituting the product materials	16	8	4	22	23	73
2. Substituting the energy source / technology	8	1	0	6	0	15
3. Optimizing the product structure	8	3	0	0	1	12
4. Designing the product considering the user experience	1	1	1	1	0	4
5. Dematerializing the product components	16	3	0	0	0	19
6. Segmenting / Dynamizing the product parts and rhythms	34	3	2	7	0	46
7. Exploiting modularity / Using standard parts	0	2	5	8	0	15
8. Exploiting the resources / Recovering the energy	6	8	0	2	0	16
9. Providing a timeless design to the product	0	0	0	0	0	0
Total	89	29	12	46	24	200

Figure 3. Number of solutions presented by students for each intersection between a Design strategy and a CE strategy. The color intensity of the cells refers to the contained value.

Figure 4 reports the total number of solutions proposed by the designers for each intersection between a design strategy (please see the rows) and a CE strategy (please see the columns).

CE strategies \ Design strategies	1. Reducing the wastes	2. Reusing the product	3. Repairing / Refurbishing / Remanufacturing the product	4. Recycling the materials of the product	5. Making the product biodegradable	Total
1. Substituting the product materials	7	5	1	11	6	30
2. Substituting the energy source / technology	4	0	1	1	0	6
3. Optimizing the product structure	6	4	1	1	1	13
4. Designing the product considering the user experience	2	4	2	3	0	11
5. Dematerializing the product components	2	1	1	1	0	5
6. Segmenting / Dynamizing the product parts and rhythms	2	0	0	0	0	2
7. Exploiting modularity / Using standard parts	5	12	20	12	0	49
8. Exploiting the resources / Recovering the energy	2	2	0	1	0	5
9. Providing a timeless design to the product	2	3	0	0	0	5
Total	32	31	26	30	7	126

Figure 4. Number of solutions presented by professional designer for each intersection between a Design strategy and a CE strategy. The color intensity of the cells refers to the contained value.

To compare the number of solutions proposed by students and professional designers for each intersection between a design strategy and a CE strategy, the bubble chart shown in Figure 5 was adopted. In this representation, the percentage distributions

of the solutions proposed by students and professional designers for each intersection are compared. The size of each student bubble was obtained by dividing the total number of solutions of the given intersection, proposed by the students, by the total number of solutions presented by the students. While in the case of professional designers, the size of each bubble was obtained by dividing the total number of solutions of the given intersection, proposed by professional designers, by the total number of solutions presented by professional designers. By overlaying the bubbles of the students and the professional designers, their size can be compared to understand which intersections one and the other went toward the most.

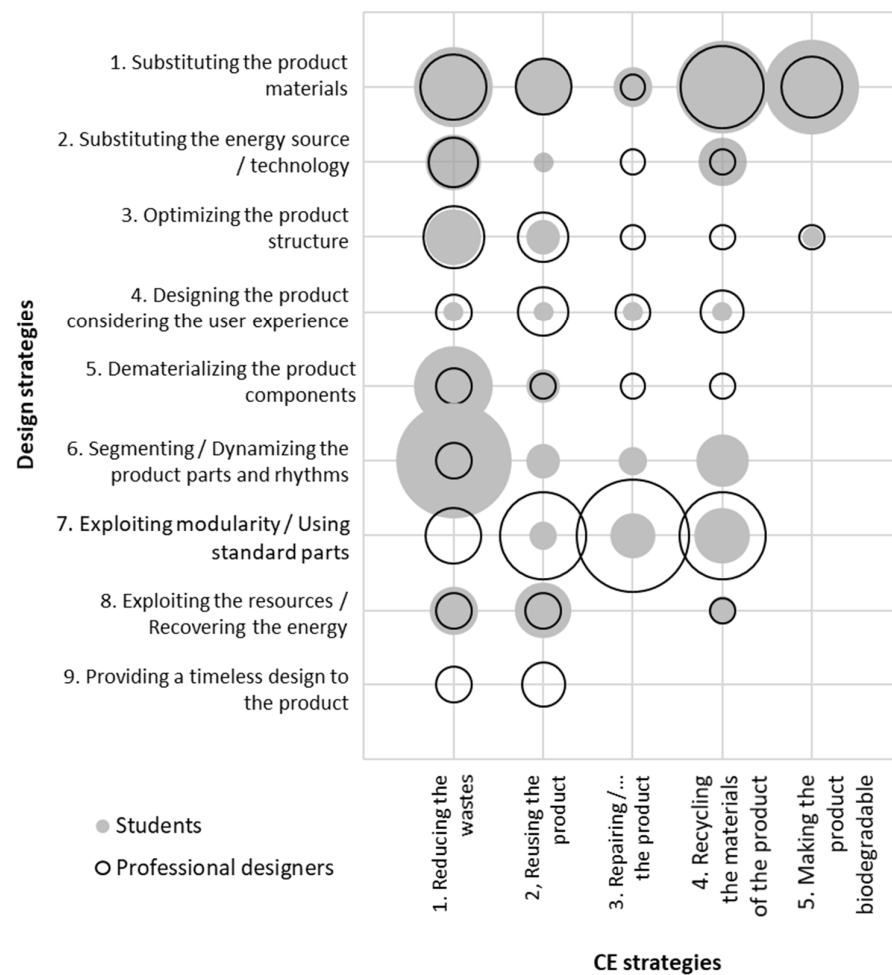


Figure 5. Graphical comparison of the percentage distributions of the solutions proposed by the students and by the professional designers related to any intersection between design strategies and CE strategies. The size of each student bubble is proportional to the ratio of the number of solutions proposed by students for an intersection to the total number of solutions proposed by students. The size of each designer bubble is proportional to the ratio of the number of solutions proposed by professional designers for an intersection to the total number of solutions proposed by professional designers.

5. Discussion

By analyzing the obtained results, several considerations can be drawn regarding the use of design strategies, CE strategies and their intersections, by students and professional designers. On a general level, although the strategies to improve the circularity and

sustainability of a product do not differ much from those experienced by students in other tests (e.g., [63]), the possibility of comparing the results obtained by them through these strategies, with those of professional designers is a novelty. Moreover, in this study, compared to [63] the perspective is also extended to common design strategies used by students and professionals not for the exclusive purpose of improving the sustainability and circularity of a product, instead of specific eco-design strategies.

The comparison of the two different distributions of design strategies obtained from students (see Figure 3) and professional designers (see Figure 4) revealed some differences. Professional designers relied more on component modularity (Design strategy N. 7), 39% of the time, and product material substitutions (Design strategy N. 1). While students primarily addressed the same Design strategy N. 1 in 37% of cases and product segmentation and dynamism (Design strategy N. 6) in 23% of cases. On a percentage level, the most distinctive differences between professional designers and students relate to the use of modularity (Design strategy N. 7), which was +21% in favor of professional designers, the use of product segmentation and dynamization (Design strategy N. 6), with 21% in favor of students, and product material substitution (Design strategy N. 1), with 13% in favor of students. Significantly less pronounced percentage differences were obtained for the other design strategies, where students almost or completely ignored the less engineering and more industrial design-oriented ones, i.e., user-centered design (Design strategy N. 4) and timeless design (Design strategy N. 9).

The greater use of material substitution (Design strategy N. 1) by students than by professional designers has already been noted in the literature. According to [64], students are more likely to adopt this strategy than professional designers, and sometimes abuse it, because they are less aware of the characteristics of materials and especially those related to environmental sustainability. According to the same authors, this “misuse” is more pronounced when students turn to biocompatible and recycled materials. A solution to this problem may consist, according to the authors, in the sharing of experience from professional designers to students or less experienced designers, so as to encourage a more conscious and targeted use of biodegradable and recycled materials.

The fact that students struggle to approach user-centered design (Design strategy N. 4) is not ignored by the literature, since it has already been noted, albeit in the more general context of engineering design by [65]. In that study, the author has indeed analyzed the difficulties that students may face in this discipline and has proposed some ideas on how to improve the teaching of design. Because of the importance of these gaps, that study contributed to show that the rethinking of the teaching methods should also be considerable.

The greater students’ interest towards the strategies of systematic innovation, i.e., segmentation and dynamization of the parts and rhythms of the product (Design strategy N. 6) could be justified by the preparation provided to the students at the University of Bergamo. The greatest influence can be found in the Product and Process Innovation course, mentioned in Section 3.2.1, which is mainly dedicated to the teaching of the TRIZ method. The novelty in this sense concerns the confidence of the students to apply these strategies in the field of eco-design, even without having convinced them a priori of their effectiveness in this regard, with objective evidences, e.g., the study of [25]. With regard to this aspect, the detailed analysis of those solutions proposed by the students and based on these strategies highlighted their creativity and innovativeness, but also their limited feasibility, to which the students’ inexperience may have contributed.

The difficulties that students may have encountered in the design for modularity (Design strategy N. 7) were already commented by [66]. Among that, the authors highlighted above all the difficulty for students to critically evaluate the real advantages arising from the introduction of modularity in a design solution, thus sometimes avoiding exploring those solutions that are also theoretically attractive.

Timeless design (Design strategy N. 9) can also be a difficult topic for students to face. In this regard, some authors have dedicated themselves to the development of

methodologies to support its teaching and its application, especially for novices. Among them, Ref. [67] introduced a framework that suggests how to modify the product structure, by introducing specific affordances, to improve the user experience. While [68] proposed strategies to avoid the problem of the user disaffection towards the Technical system when her/his needs change over time. Their goal is to support the design of the Technical system with more considerations for the future needs of the user and with greater regard to the user experience.

The distributions of the CE strategies considered by the students (see Figure 3) and the professional designers (see Figure 4) were also different. The students focused mainly on waste reduction (CE strategy N. 1), in 45% of cases, and towards recycling of materials (CE strategy N. 4), in 23% of cases. While the professional designers, on the other hand, followed a more homogeneous distribution, with percentages ranging between 21% and 25% for all CE strategies unless for N. 5. The most marked differences between professional designers and students were found in the case of waste reduction (CE strategy N. 1), with +19% in favor of students and product remanufacturing (CE strategy N. 3), with +15% in favor of professional designers. Finally, the biodegradability of the product (CE strategy N. 5) was overall little sought after by both students and professional designers.

By comparing instead the intersections between the design strategies and the CE strategies of students and professional designers, it is possible to obtain more detailed considerations and a better understanding of how both faced the CE problem.

The material substitution (Design strategy N. 1) was considered by students and professional designers to realize the same CE strategies with a similar interest, except for a rather small difference when looking for the biodegradability of the product materials (CE strategy N. 5). Furthermore, this design strategy was practically the only one, apart from a few contributions, to be used to implement this CE strategy.

The segmentation and dynamization of the parts and rhythms of the product (Design strategy N. 6) was exploited by the students above all to reduce waste (CE strategy N. 1). Even professional designers have resorted to this design strategy for the same purpose, albeit with much less interest. Furthermore, only the students used this design strategy for other purposes as well.

The use of modularity and component standardization (Design strategy N. 7) was considered much more by professional designers than students, especially to favor product remanufacturing (CE strategy N. 3) and product reuse (CE strategy N. 2). Furthermore, only professional designers used this design strategy to reduce waste (CE strategy N. 1).

The product dematerialization (Design strategy N. 5) obtained a rather homogeneous distribution of the CE strategies by professional designers, although limited to quite small numbers. Instead, the students used this design strategy in a much greater way, even if specifically, to reduce waste (CE strategy N. 1), apart from a few exceptions for the reuse of the product (CE strategy N. 2).

The design of the product according to the user experience (Design strategy N. 4) obtained similar distributions according to the CE strategies in students and professional designers, although with much higher numbers in the latter group. Finally, other considerations on the distributions of the intersections between the other design strategies, which have been considered in a more marginal way, and the CE strategies, in students and professional designers, can always be deduced from the graph in Figure 5.

In particular, even from the comparison of the results obtained by professional designers in relation to the different application fields, further considerations can be drawn. Material substitution is exploited to a similar extent in both product design and buildings. The use of modularity and standard parts is also exploited in electronics and appliances, where the same components are used for different devices. Furthermore, even in product design and buildings, where this strategy is still used, some standard components are electronic. There is also the use of user-centred design in household

appliances. As regards the CE strategies, we noted an intersection between the reduction of waste and electronics, also motivated by the WEEE (Waste Electrical and Electronic Equipment Directive) directives ([57,58]). Instead, the design for repairability was heterogeneously associated with all the different application fields.

Even entering into the merits of how the design strategies have been used specifically to facilitate the transition to CE, other considerations can be added. In the material substitution, the introduced materials require less energy to be restored, such as the replacement of alumina with silica aerogel in the air dryer. Another use of this strategy concerns the introduction of qualitatively better materials, with improved mechanical and chemical properties, as well as higher purchase costs, to increase the operative life, as in the case of coatings. To provide biodegradability, completely natural materials or materials derived from natural ones such as polylactic acid (PLA) substitute the synthetic ones. The energy source substitution has been used primarily to seek more energy efficient transportation means or technologies and with a lower consumption of auxiliary materials to reduce waste. In some cases, the choice of the new technology is also exploited to implement cogeneration. The optimization of the product structure was mainly used to reduce the mass of the product and therefore the waste of material. The user-centred design is exploited for different reasons. On the one hand, to extend the operative life of the product, both by making the user fonder of the product thanks to an improved feeling, as well as timeless design, and making sure that the user can use the product in a more suitable manner. On the other hand, to improve the product by making its own structure able to communicate to the user how to properly disassemble the parts to reuse/recycle. The dematerialization of the structures is related to the reduction/elimination of solid waste, preferring to dispose liquids and gases. Segmentation and dynamization are used to focus the use of the resources (i.e., auxiliary materials and energy) to reduce waste and better regulate the operating rhythms of the product to increase its duration. The modularity of the components is also implemented to facilitate disassembly, reuse and recycle. Similarly, the introduction of standard parts facilitates their reuse in other compatible products.

Finally, the results provided by this study can also be compared to the roadmap for the international sustainable design research community proposed by [69]. In this case, the enrichment of teaching students on the different approach of professional designers to eco-design can be understood as an easy to implement and short-term intervention. In particular, the results provided are useful in phase 2 of the roadmap, to identify the needs from industry and providing literature review.

6. Conclusions

This paper proposed a comparison on which design strategies are used most, to implement different CE strategies by students and professional designers. The data of the first ones were collected by analyzing works from year projects and theses, while those of the latter derive from selected scientific articles. By comparing the distributions of the design strategies, the CE strategies, and their intersections, different considerations about the approaches preferred by students and professional designers were collected, as well as some of their difficulties.

The main novelties of this study are the explored intersections between the Design strategies and the CE strategies, because the first ones are not specifically aimed to improve sustainability, differently to other studies comparing eco-design strategies and CE strategies. The comparison between the students' and designers' solutions is also a novelty if reported to this aim. In addition, the obtained results could also be useful to provide part of the knowledge base to some open-points of CE teaching programs outlined by some authors.

The obtained results should be read in relation to the main limitations of this study. The classification of the case studies according to the followed strategies was carried out manually and this phase requires a certain experience of the evaluators. In the specific

case, this experience was gained by the authors in about ten years of applications of eco-design and problem-solving methods in real industrial case studies. The considered case studies, although varied, refer to few application fields and with a rather unbalanced distribution towards some of them. The considered students, although belonging to two different universities, are mainly related to the Italian educational context.

The analysis of these results revealed the possibility of dividing the design strategies into three distinct groups based on the preferences of students and professional designers.

1. The design strategies deriving from systematic innovation, and from the TRIZ method, were preferred by students quite clearly.
2. The design strategies most typically referable to industrial design, i.e., exploiting components modularity, user-centered-design and timeless design have been preferred by professional designers.
3. The design strategies related to the most routine design, i.e., materials substitution, reducing resources and energy consumption and structural optimization, have been used more or less equally by both students and professional designers.

These results could have some implications for teaching engineering design to students. The teaching of more theoretical concepts could in fact be enriched with case studies aimed not so much at exemplifying these concepts, but at discussing the differences in the approaches of students and professional designers. In this way it is also possible to enrich the presentations of the methods with the ways according to which they are normally applied by professionals in the industry. Furthermore, the intersection between traditional design and CE is useful for making students understand the potential relationships and synergies between the two of them, since in many cases they are taught in a separate way, relegating CE specifically to eco-design.

The most obvious gap to be filled concerns the reluctance of students to resort to user-centered design and timeless design, although it should be confirmed whether this lack is due to a generic limit in approaching design according to these strategies or just eco-design. Secondly, the students' use of systematic innovation strategies is appreciable, but the gap with professional designers could mean that the obtainable solutions that are not applicable or achievable are different from those proposed. Spreading the knowledge of these strategies, in a greater way, even to professional designers could also be useful to dispel this doubt, verifying whether the distribution of their design strategies should level off.

Furthermore, the differences in the approaches of academia (more theoretical towards the use of methods for systematic innovation such as TRIZ) and industry (more pragmatic in considering strategies and best practices) have also highlighted a possible contamination of the first towards the second. Indeed, several positive results obtained by students by exploiting methods for systematic innovation, such as the improvement of creativity, quality and numerosity of the proposed ideas, could stimulate their application in industry, e.g., the introduction of courses and the software development.

The main future developments of the methodology could therefore be the proposal of new tests involving a greater number of students and new case studies. Finally, it might be interesting to repeat the same tests after having trained the students more in the rudiments of industrial design and professional designers in systematic innovation.

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