education sciences

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Article

Eco-design and Eco-efficiency Competencies Development in Engineering and Design Students

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Received: 30 April 2019; Accepted: 5 June 2019; Published: 7 June 2019

Abstract: The development of vital competencies and a mindset to rethink products, production, and business models in engineering and design students is presently of great importance. These future professionals will play a key role in the development of sustainable products. Within Eco-design and Eco-efficiency curricular unit, an assignment was developed that consisted of the development of an eco-design and eco-efficiency study of a given product, provided by a real industrial company. In this paper, the challenge description and application are reported, as well as the key conclusions.

Keywords: circular Economy; eco-design; eco-efficiency; engineering education

1. Introduction

There is a need to produce goods with a lower impact on nature, reducing the use of primary raw materials, minimizing energy consumption, and promoting long and circular product life cycles [1–4]. These are the joint challenges of Industry 4.0 and Circular Economy, that, together, will promote a production and consumption paradigm shift [5–9].

Industry 4.0 is slowly changing the way we produce goods and services in order to achieve greater productivity using less material and fewer energy resources. The "Industry 4.0" philosophy seeks to introduce the technological advances that have been achieved in recent years in the field of sensor and control, computing, and automation processes, creating the conditions for new product development processes and new forms of production, including integration of conventional and advanced manufacturing technologies, such as additive fabrication [5]. However, this philosophy of industrial development must also be based significantly on the re-use of raw materials and making use of eco-design and eco-efficiency strategies [6,7]. The price of raw materials is continuously increasing, because of its growing scarcity in many cases, but also because of the social and environmental costs that the extraction and production of new raw materials entail. It is from the integration of these different perspectives that companies can better embrace the circular economy.

The concept of circular economy aims to respond to the challenges of maintaining life quality, without exterminating humanity and the planet [8]. A circular economy is, in principle, regenerative and restorative. Its goal is to keep timely products, components, and materials at the highest level of utility and value. This means that a product, after its use, is not discarded for a landfill or for incineration. It means that after its lifetime, the product continues its life cycle, to be repaired or transformed, giving rise to a regenerated product or to raw materials that will constitute a new product. With this, we keep these products, components, and materials in a closed circle of economic utility, without increasing exponentially the need for new raw materials, nor waste of materials for landfills [9].

Circular economy is perceived to induce regenerative industrial transformations that will pave the way to achieve sustainable production and consumption. The ambition is that the evolution of circular economy based industrial production will have a positive impact on the environment and will also contribute to economic growth [10]. As society increasingly seeks the bases of sustainable living, we are

becoming more aware of the key responsibilities that consumers and organizations have. A spotlight shines on company behavior and reveals the importance of encouraging firms to use their resources as efficiently as they can. Nevertheless, companies may lack the information, confidence, and capacity to move to a circular economy, due to a lack of indicators and targets, awareness of alternative circular options, and economic benefits, and, especially, the existence of skill gaps in the workforce and lack of circular economy related curricula [11]. The development of vital competencies and a mindset to rethink products and production settled in these new concepts in mechanical engineering and product design students is of fundamental importance. It is mandatory that these future professionals play a key role in the development of sustainable products.

There are many initiatives underway to implement the concept, especially in legislative and governmental bodies, NGOs, and consultancy firms, but real practical established approaches are still under construction [8] and need to be supported by examples of new business models [7] that have these concepts in their base. As an example, imagine diamond cutters for cutting glass or ceramic material. The conventional business model goes through a manufacturer, possibly in China, to produce the metal milling cutters, and the same manufacturer, or another, will apply the coating of synthetic diamond microcrystals. Once the production is finished, they will be sold to a company that will use them until the diamonds' cutting efficiency decreases considerably. The final destination of these cutters is the garbage or, at best, a sale for the recovery of the metal. However, these cutters could be re-coated with diamond multiple times, always having the same cutting efficiency as the completely new cutters. With this business model, the material and energy expended to manufacture the metal part would be spared. Despeisse et al. [12] points that the characteristics of additive manufacturing align well with sustainability and circularity principles and hold significant promise for moving society in a more sustainable direction, as these characteristics can be used for repair and remanufacturing and the production of printing filaments, including the commercialization of filament that contains recycled materials, and recycling systems for creating filament.

The literature points out that the well-established eco-design guided by the life cycle assessment of a product and eco-efficient production are vital for the transition to a circular economy [13–19]. Eco-efficiency is based on the idea that fewer natural resources should be used to generate the same, or a greater, amount of economic activity. Whatever the setting, objectives are loosely grouped around sustainability. Eco-efficiency can be seen as a tool for sustainability analysis and development [18]. Eco-design is defined as the integration of environmental aspects into product design and development with the aim of reducing adverse environmental impacts throughout a product's life cycle [19]. It must focus its attention on the phases of the product's life cycle that most significantly affect the environment, so that upon re-designing the product, its environmental impact can be greatly reduced. Therefore, integrating eco-design and eco-efficiency into the product development process can contribute to the development of vital competencies and a mindset to rethink products and production process that will potentially assist the transformation of linear to circular economic business models and can offer several advantages to industry and public organizations, such as economic benefits, legislation fulfilment, innovation and creativity promotion, public image improvement, and employee motivation enhancement.

Although eco-design and eco-efficiency concepts are well-established in both theory and practice, and across a wide variety of contexts, education for sustainable development is quite a challenge, particularly to educate future engineers in this manner, as this type of education demands a departure from the current disciplinary and subject-focused teaching that predominates current educational paradigms, particularly in engineering education [20,21]. Simply integrating conceptual topics into existing courses is not enough, as the current paradigm's approach is too reductionistic to handle multidimensional problems [22,23]. Instead, students must learn to employ system thinking to fully comprehend the challenges. Furthermore, in addition to the key eco-design and eco-efficiency concepts competencies, students must also build an awareness of societal and economic aspects [23].

Different approaches for education and learning have been developed in similar contexts, including gamification methodologies [23–25]. Nonetheless, the integration of teaching and learning in higher education with its surrounding societal reality, in an embeded way, is particularly critical to the development of future professionals with sustainability literacy, as these future professionals will become the agents of change in their workplaces and personal lives [26]. Work-based learning at higher education levels has been highlighted as a pressing need [27–30]. In the current context, it is imperative that students learn how the subjects they address in the classroom are related to the real world [28]. Simultaneously, by putting them in touch with industry, these students are given the possibility to explore career options. Additionally, from this university–student–society interaction, companies have the possibility to interact with potential future employees who will have a better knowledge of the workplace. Higher education institutions, on the other hand, benefit from an increase in student motivation and can improve the relationship between schools and the community. In addition, curricular interaction with society is an ideal methodology to relate the content taught, whether fundamental or applied, to the challenges of the society and achieve a balance between the fundamental technical-scientific competences and the transversal competencies currently required by employers [29].

Having, therefore, the double objective of addressing eco-design and eco-efficiency to promote a circular economy mindset and the integration of teaching and learning with the surrounding industry, the Eco-design and Eco-efficiency (EDEE) curricular unit at the University of Aveiro (Portugal) has been promoting the development of eco-design and eco-efficiency projects for selected products in their industrial production environment, presented by industrial entities of the Aveiro region, to promote an entrepreneurial mindset for the creation of sustainable products and processes, in scope with industrial trends of digitalization and circularity.

In this work, the description of the assignment and its application is reported, as well as the key results obtained. It is relevant to state and analyze the key findings, including if the assignment has contributed to the goal of promoting an entrepreneurial mindset for the creation of sustainable products and processes, as well as promoting a better comprehension of workplace and industry environments.

2. Methods

The Eco-design and Eco-efficiency (EDEE) curricular unit at the University of Aveiro is an optional discipline offered, mainly, to Mechanical Engineering and Product Design and Engineering master students. The case study presented in the present paper has taken place in the academic year of 2018–2019 (semester 1), and the class was composed of 49 students, of which 37 were Mechanical Engineering students, 9 were Product Design and Engineering students, 1 was an Electronic and Telecommunications Engineering master student, and 2 were Mechanical Engineering Erasmus program exchange students (one from Germany and another from Italy). The curricular unit is organized and lectured by one teacher, but several other university teachers and researchers are involved in the connection with the companies.

The main objective of the EDEE course is to promote an entrepreneurial mindset for the creation of sustainable products and processes, in line with industrial trends of digitalization and circularity. Students will be challenged to develop a new product, or rethink a previous product, to decrease resource use intensity, giving priority to the use of renewable materials, including recyclable and/or bio-based materials, and with less hazard and risk (for humans and the environment) and better reuse of materials. To this end, eco-design and eco-efficiency concepts and tools, and their applications in the different stages of engineering and product development, are covered, as well as rules and regulations. Specific issues addressed during the semester include product development and industrial trends; eco-design and eco-efficiency concepts and tools [1–4]; life cycle assessment—ISO 14040 and 14044 standards [31–33]; industrial environmental management systems—ISO 14001:2015 standard [34]; energy management in manufacturing—ISO 50001:2018 standard [35]; lean manufacturing [36,37]

and other principles that can assist efficiency production; and product and business design for a circular economy.

The proposed assignment, described in this paper, is very much aligned with the curricular unit objectives. The development of the assignment can be divided into three parts, as illustrated in Figure 1. The first stage is to clearly identify the product and fabrication process (as done by the company). Second, students must perform an eco-design analysis of the product and an eco-efficiency evaluation of the production process. This should be developed as a Life Cycle Assessment (LCA) of the product [31–33], considering the product from cradle to grave. For the LCA analyses, students are encouraged to use Ecolizer (http://ecolizer.be/) or openLCA (http://www.openlca.org/) software. The first is a free online platform that enables a simple comprehensive inventory and environmental impact calculation. The second is an open source and free software for sustainability and life cycle assessment. Although both present limitations for a complete product LCA analysis, they have the necessary requirements for the assignment. Students may calculate the overall environmental impact but also the impact of each phase in the life cycle of a product so that a life cycle phase with a high environmental impact can be tackled or compare the scores of different products with each other.

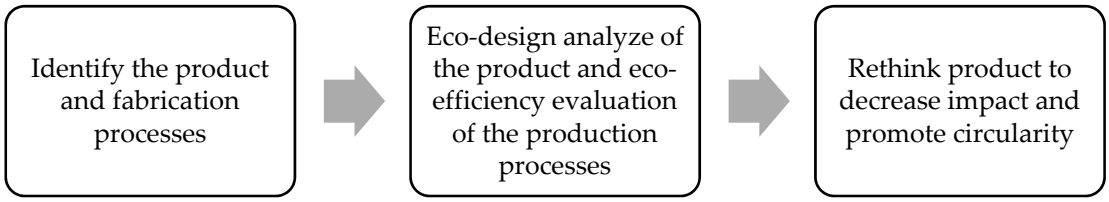

Figure 1. Assignment development stages.

Finally, in the third part, the proposals to decrease the product's impact should be projected. In this last stage, students should rethink the product to decrease the resource use intensity, giving priority to the use of renewable materials, including recyclable and/or bio-based materials, and with less hazard and risk (for humans and the environment) and reuse of materials. "Modularization" of the components, allowing easy disassembly, recovery, reuse, and end-of-life screening (standard components) may be considered, as well as the definition of recycling, reuse, and life-cycle extension criteria, considering possible useful applications of by-products and waste. Groups should pursue ways to attain more efficient and cleaner production models, producing more, at lower prices, with fewer resources, less waste, and less of an impact on the environment. The use of RETScreen (https://www.nrcan.gc.ca/energy/software-tools/7465), a clean energy management software, is given as an example of a tool to use to assist in the pursuit of increased ecoefficiency production. Proposals to convert the business model to a circular economy business model are also encouraged.

The assignment must be developed respecting the pace of the following milestones, distributed homogeneously throughout the semester:

- Milestone 1: Product and production description (current situation). A 3 minute video explaining the product and the production process must be delivered.
- Milestone 2: Life cycle assessment of the product (current situation). A 5 minute video presenting the current LCA of the product and production process must be submitted.
- Milestone 3: Eco-design of the product and production processes eco-efficiency. A 5 minute video explaining the eco-design and eco-efficiency proposals must be handed.
- Milestone 4: Full assignment presentation and discussion, in the company to the company people.
- Milestone 5: Final report delivery. The technical report must have a maximum of six A4 pages complemented with the needed attachments.

Although class materials are all in English, the official language of the curricular unit, the deliverables, presentation, and discussion above mentioned can be in either English or Portuguese. Also, the milestone deliverables can be reformulated at any time until the final exam period.

Because the development of the assignment needs access to production data to properly instruct the inventory stage of the life cycle assessment, students and other people involved in this assignment must compromise to keep all information accessed and deliverables confidential. Complementarily, if the assignment creates truly innovative results that may be the object of intellectual property registration, the copyright will be given to the university and the company. The copyright given to the university will not jeopardize the rights of the students, as well as the teachers and other involved staff, to be designated as creators, inventors, or authors of the invention or creation.

The assignment deliverables were organized by the class teachers on a private webpage. The assignments were developed in groups of 4 to 5 persons, and each group had to be composed of students from at least two different courses. This assignment represented 60% of the final grade of the curricular unit, whether students were in discrete or final evaluation. The additional 40% of the grade was obtained by an individual written test.

For the assignment development, each group selected a product/company from a given pool. This products and companies were arranged by the curricular unit teachers and are presented in Table 1.

Table 1. Companies and products studied in the assignment.

Company	Location	Product(s)
Composite Solutions	Vagos	"Waterlily"
Levira	Oliveira do Bairro	Office desk and cabinet
Mistolim	Vagos	Detergent Pack
Moldit	Loureiro	Gardening vase
OLI	Aveiro	Toilet flush (bathroom)
PNH	Águeda	Restaurant toaster and fryer
Ramalhos	Águeda	Bakery oven

To evaluate the perception and appreciation of the learning and teaching outcomes by the involved agents—the students, corporations, and teachers—simple open-ended questions surveys where developed. The objective was to get information about the assignment contribution to the proposed goals. Is the assignment contributing to the proposed goals? Are students being able to connect the subjects that they learn in the classroom with the challenge case and develop a better comprehension of the workplace? Are students motivated by the assignment? Are companies satisfied by the technical results proposed and with the interaction with students? Is the university's business relationship improved? Are students' fundamental and transversal soft skills improved?

For students, making use of an online form tool, one single open question was placed:

> "What is your global appreciation of the assignment? Is this type of evaluation justified in a course of Eco-design and Eco-efficiency? Do you consider that this type of work is relevant to your training? Do you think that initiatives of this kind contribute to a greater alignment between the university and society? What were the most positive and the most negative point of the assignment? What aspects could be improved?"

For companies, again one single open question inquiry was placed and sent by email:

> "What is your global appreciation about the assignment that students developed within your company?"

In the case of the teacher and collaborators, the register data was compiled in groups, as part of the assignment self-evaluation routine.

3. Results

The different surveys resulted in 10 responses from students (out of 49 students, representing about 20%) and five responses from companies (out of 7, representing about 70%). The collected data was analyzed and resumed in Tables 2–4 in order to highlight the main ideas.

Table 2. Resume of students' responses to the inquiry.

Students Main Appreciation about the Assignment
"The assignment showed us the difference between an academic assignment and an assignment for a company."
"We realized that some concepts cannot be applied linearly in the company."
"There should be more initiatives such as this one so that we could understand how companies work."
"I enjoyed doing the work. It put us close to the industry and facing real production processes."
"Having a colleague from a different course in the group was very useful since they have complementary experiences and skills."
"It would be good to see some of our solutions being implemented by the company and to have information on how the solutions changed the organization."
"The company contact sent us the inventory information very late."
"They didn't send us all requested information."
"This challenge did not add or contribute to a deepening of the topics taught in this curricular unit."

Table 3. Resume of companies' responses to the inquiry.

Companies Main Appreciation about the Assignment
"The fact that the students have to analyze the investment and the return is very important."
"it's a pity we did not have more time to dedicate to you."
"Be persistent."
"Although the solutions presented may not be directly applicable, they are the source of new ideas."
"The challenge is a great way for future professionals to get to know our company."
"students must be more precise in what information they need us to provide."

Table 4. Resume of teachers' responses to the inquiry.

Teachers Main Appreciation about the Assignment
"The comprehension of the production processes and the application of life cycle assessment methodologies is better attained."
"The challenges also contributed to the promotion of student's transversal skills."
"In general, both students and companies consider that the challenges have an added value."
"the work helps to link classroom teaching with the factory shop floor practice."
"students begin by having a lot of resistance to this kind of assignment."
"To the majority of students, this was the first time that they had to produce and edit a video of this type."
"Three video deliveries ended being not so positive. A poster delivery could be proposed instead, contributing to a new skill request."
"Intermediate milestones were very important to promote a continues work in the assignment during the semester."
"arranging proper companies and products is complex."

4. Discussion

Globally speaking, students attribute value to the assignment and even suggest that more curricular unit assignments could be developed with interaction with the industrial sector. Although some initial difficulties understanding the overall assignment and some communication difficulties were reported by student and by companies, the overall sense is that the assignment created the conditions for students to acquire a critical and innovative sense in relation to the way that products are manufactured, being, therefore, better prepared to develop optimization projects, problem resolution in this technology area, and development of an entrepreneurial project that incorporates eco-design and eco-efficiency philosophies and may lead to the adoption of circular business models.

Most of the companies, if not all, pointed out the importance of merging the technical proposals with the required investment, as well as the training of staff and revenue of the investment. This was considered an added value of the assignment, and it was recommended that teachers reinforce this point in their classes along with the curricula. The openness of companies to receive students and interact with them after the first visit depended very much on their own availability, but company personnel always encouraged students to be pro-active and persistent to attain the information needed. Companies also recognized that the assignment was a good source of new ideas and solution proposals, besides it being a good opportunity for them to interact with potential future collaborators. These findings are well aligned with the literature [28,30].

The teachers and other staff involved with the application and management of the assignment consider it to be a good methodology to open students' mindsets to the challenges they will face in the near future in the workplace. This assignment promoted technical competencies related with product and production eco-design and ecoefficiency, but also competencies that were not yet developed within their academic path, such as a direct relationship with companies. Probably because of the originality of the assignment, the number of students reluctant to do the assignment was considerable. Nevertheless, at the end of the work, it was considered a positive experience by most. Some students still considered the assignment a waste of time and felt that it did not contribute to their academic development. The logistics of the assignment are complex. Not all companies are willing to receive a group of students and share with them their production details. Similar experiences have been reported elsewhere [38–42].

Intermediate milestones were very important to promote a working pace. The first three milestones were delivered in short length video format. To the majority of students, this was the first time that they had to produce and edit a video of this type. It was considered a good strategy to also promote new transversal skills. In the future, the third milestone may be requested in poster format instead of video, so skills in poster production can also be developed and the number of videos requested might be reduced. The mandatory blending of students from different courses and different backgrounds was not well accepted at first but was later considered a positive point.

In a nutshell, having in mind the questions formulated to evaluate the perception and appreciation of the learning and teaching outcomes by the involved agents, it can be considered that the assignment contributed to the proposed goals of addressing eco-design and eco-efficiency to promote a circular economy mindset and the integration of teaching and learning with the surrounding industry. Students were motivated by the assignment and were able to connect the subjects that they learned in the classroom to the challenge case and develop a better comprehension of the workplace, as well as improve their fundamental and transversal soft skills. Moreover, companies were satisfied by the technical results proposed and with their interactions with students. As new university business collaborations are successfully developed, their relationships will be improved.

5. Conclusions

Today's engineering and design students will be the builders of tomorrow's products. Sustainability is a responsibility of each inhabitant of planet Earth, but engineers and designers play an important role in this. It is, therefore, of vital importance that engineers develop competencies and a mindset to rethink products, decrease the resource use intensity, pursue ways to attain more efficient and cleaner production models, and convert linear business models to circular economy business models.

The proposed challenge contributed to the goal of integrating societal challenges within students' mindsets while developing their technical and transversal skills. The assignment created the condition for a real interaction between students and industrial agents, and through them, between the university and the companies, which have already led to new research collaborative projects. As reported by the literature, collaboration between universities and the different actors of the economic environment leads to a series of benefits that have a favorable impact on business competitiveness and university curricula [27–30,38–42].

It must be noticed that the findings presented here were acquired from one single application of the assignment model. It is intended to repeat the present model, with the incorporation of the improvements highlighted in this paper, in future academic years.

Funding: The research here presented was supported by the projects UID/EMS/00481/2019-FCT - FCT - Fundação para a Ciência e a Tecnologia; and CENTRO-01-0145-FEDER-022083 - Centro Portugal Regional Operational Program (Centro2020), under the PORTUGAL 2020 Partnership Agreement, through the European Regional Development Fund.

Acknowledgments: The author greatly thanks the openness of the companies involved.

Conflicts of Interest: The author declares no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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