Incorporating Life Cycle Assessment and Ecodesign tools for Green Chemical Engineering: a case study of competences and learning outcomes assessment

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Abstract

Chemical engineers assume a broad range of functions in industry, spanning the development of new process designs, the maintenance and optimization of incumbent systems, and the production of intermediate materials, final products and new technologies. The technical aptitude that enables chemical engineers to fulfill these various roles along the value chain makes them compelling participants in the environmental assessment of the product in question. Therefore, the introduction of life cycle assessment (LCA) and ecodesign concepts into the chemical engineering curriculum is essential to help these future professionals to face design problems with a holistic view of the technical, economic, social and environmental impacts of their solutions. The teaching of these and other disciplines by means of student-centered methods, based on a holistic structure, have demonstrate better teamwork and communication skills. For that reason, this paper proposes a Micro (Assess-Analyze-Act) (M-3A) model of assessment mainly focused on closing the loop of learning activities. This model has been applied to an ecodesign case study of the Master of Chemical

Engineer with positive feedback of the students. They felt that the approach has allowed them to utilize their analytical skills in quantifying a situation before applying other subjective measures, and that the public discussion of the results was a satisfactory element for improving their communication skills. Moreover, the students found that the workload was nicely adjusted, highlighting the acquisition of 4 competences preferentially: teamwork, creativity; relevance of environmental issues and initiative and entrepreneurship. Finally, the students suggest that the application of this methodology into their degree could motivate future students improving their performance.

1. Introduction

Recently there has been an increased societal awareness of the way human society is progressing and the current and future associated environmental impacts (Harris and Briscoe-Andrews, 2008). In this sense, industrial activities, such as the chemical industry, resulted in the past century in huge advances, however, it is often viewed by the general public as causing more harm than good (Muñoz, 2012). . Sustainable development, and in less extend, green chemistry and industry ecology, have become keystones of environmental policy, and leading principles for resource management.

Industrial ecology is defined as the practice of applying the principles of ecology to industrial and regional economic development that offers considerable promise for improving economic performance while reducing industry's environmental and ecological footprint (Das and Cabezas, 2017). The implementation of this ecological or systems approach that is focused on a part of sustainability,

can buy time for the necessary societal evolution (Reuter et al, 2005).

On the other hand, there is world-wide demand for more efficient products to reduce energy and resource consumption, providing the EU legislation on ecodesign (EC, 2009) and labelling (EU, 2017) an effective tool to meet this challenge. In fact, ecodesign strategies support industrial competitiveness and innovation by promoting the better environmental performance of products (EC, 2009).

In this general context of pressures of rising population and declining resources a key profession to resource use and development is engineering. Engineers equipped with the skills to develop sustainable technologies (Harris and Briscoe-Andrews, 2008), will be called upon to design more eco-efficient systems and technologies, to deal with ever-increasing uncertainty, and to consider the social and economic impacts of engineering choices in both a national and global setting (Huntzinger et al., 2007). The successful integration of sustainability into engineering curricula and the inclusion of activities that enhance their initiative, versatility, creativity and innovation require a change towards new methodologies and ways of approaching the teaching-learning binomial (Feijoo et al., 2017). In addition to this, students need not only the knowledge to generate effective engineering solutions; but also, the intellectual development and awareness to understand the impact of their decisions. The education challenge is to address methodologies that allow integrating technical and evaluation tools for learning and motivating approaches.

Particularly, chemical engineers are uniquely placed to act upon these concerns because they have complementary skills in traditional engineering, process modelling, and economic, environmental and social analysis (Harris and Briscoe-Andrews, 2008). Chemical engineers assume a broad range of functions in industry, spanning the development of new process designs, the maintenance and optimization of incumbent systems, and the production of intermediate materials, end products and new technologies. The technical aptitude that enables the chemical engineer to fulfill these various roles along the value chain makes them compelling participants in the environmental assessment of the product in question (Provo et al., 2013). Therefore, chemical engineers can and should be the professionals who lead this challenge. The chemical engineering community is addressing the subject by gearing much of the recent academic research toward sustainability. In fact, in 1990 the global Society of Environmental Toxicology and Chemistry (SETAC) organized a workshop on "A Technical Framework for Life cycle Assessment" that was followed by series of workshops where central elements of LCA methodology was discussed (Hauschild et al., 2018). The series culminated in a Code of Practice workshop, leading to the development of the first official guidelines for LCA (SETAC, 1993a). This guideline were formal standardized in 1996 by the International Organization of Standardization (ISO) in the four ISO standards 14040 (principles and framework), 14041 (goal and scope definition), 14042 (life cycle impact assessment), and 14042 (life cycle interpretation), and rearranged in 2006 in the ISO 14040 and ISO 14044 (Fullana and Puig, 1997).

Many professional organizations are establishing Sustainability forums and consortiums, as well as renowned universities have included courses in sustainable engineering, industrial ecology and ecodesign in their engineering/technology curriculum to better prepare tomorrow's chemical engineering professional (Sriraman et al. 2017).

A unifying thread that runs through such courses is a "life cycle" based holistic approach to product, process and infrastructure design. In general, the processes, across many industries, are/will be analyzed using life cycle assessment (LCA) lens - cradle to grave analysis. LCA involves the consideration of inputs (raw materials and energy) and outputs (products and emissions) for each stage of the cycle over the useful life of a product or process. We feel that future processes conceived and developed by life cycle analysis, if implemented well, could strengthen the ethical and humanitarian values that the engineering and business communities should strive toward. Application of appropriate pedagogy is key to active student engagement in the learning process and to the application of concepts to the solution of technical problems.

Chemical engineering curriculum has traditionally been delivered in conservative manner, despite traditional lectures have argued to be ineffective (Glassey et al., 2013). Evidences suggests that, the students who had proceeded through the student-centered methods, are generally motivated by it and demonstrate better teamwork and communication skills (Calvo and Prieto, 2016), higher levels of confidence in their problem-solving abilities and a greater sense of community among themselves, among other capabilities. The most common methodologies are cooperative/collaborative learning, problem-based learning (PBL), web-based learning team-based learning (TBL) and enquiry-based learning (EBL) (Najdanovic-Visak, 2017). The latter approach is widely used in medical education, but also in engineering application in which has been introduced via industrial relevant case studies through the whole curriculum. This pedagogical strategy is centered on students, who learn by tackling engineering problems and working in groups (Huijuan et al., 2017). Starting by posing questions, problems, or scenarios and with the guidance of a facilitator, the students identify their own questions and acquire the requisite knowledge. EBL is used as an umbrella term to cover forms of learning driven by a process of enquiry, including the more widely known approach of problem-based learning (PBL) and the project-based learning (PJBL) (Glassey et al., 2013). Despite the philosophy of inquiry is common in the EBL, PBL and PJBL approaches, they use it from different perspective, differing on the main principal, the procedure and the outcomes. The main difference between all these methods is that whereas

EBL is the art of questioning and raising questions, PBL is the art of problem solving and PJBL is based on a learning process whereby the student is working on authentic or real-word problems to get a tangible product (Oguz-Unver and Arabacioglu, 2014).In this paper a hybrid problem-project based pedagogical approach to teaching sustainable engineering and industrial ecology is described. The work covers two main aspects previously mentioned: i. a problem based learning methodology to promote self-directed student learning of key course concepts in which teams of students solve problems in product design, allowing to introduce motivating factors; and ii. a Micro (Assess-Analyze-Act) (M-3A) model of assessment, mainly focused on closing the loop of learning activities, in order to evaluate and, where appropriate, to improve the teaching-learning model by means of competences and learning outcomes assessment.

2. Methodology

Figure 1 displays the conceptual diagram of the work methodology. According to the scheme shown, it is possible to distinguish: i. the definition of the studies program, the course and its objectives (fundamental to defining the framework and context); ii. the structure of the proposed project and the relationship with the competences of the course; and iii. the model of assessment focused on closing the loop of learning activities.

This methodology has been applied to the chemical degree, however, as in the case of other student-centered methods, it can be used in other engineering and science degrees. In fact, according to Glassey et al. 2013, the enquiry-based learning, problem-based learning and project-based learning approaches are typically applied in medical education and also offer an extensive use in engineering fields: space engineering (Rodriquez J et al. 2015), mechanical Engineering and Biomedical Engineering (Perrenet et al., 2010), electric engineering (Yadav et al., 2010) and electronic engineering (Mitchell and Smith, 2008). In addition, this methodology has been applied to other fields like music education studies (Lasauskiene and Rauduvaite, 2015).

In the first step, the subject is defined by a series of eco-design and transversal competences. The former includes the acquisition of knowledge about life cycle assessment methodology, environmental sustainability and ecodesign, whereas the transversal competences are focused on the ability of solving new problems and communicating environmental information, having critical thinking and being self-sufficient.

Based on these competences the students will be able to design and defend in an open session their ecodesign project. Finally, in the third stage the learning and competences acquired by the students will be assessed using the M-3A model. This is an iterative process, in which based on the results of the evaluation and set of measures are proposed to improve the outcomes.

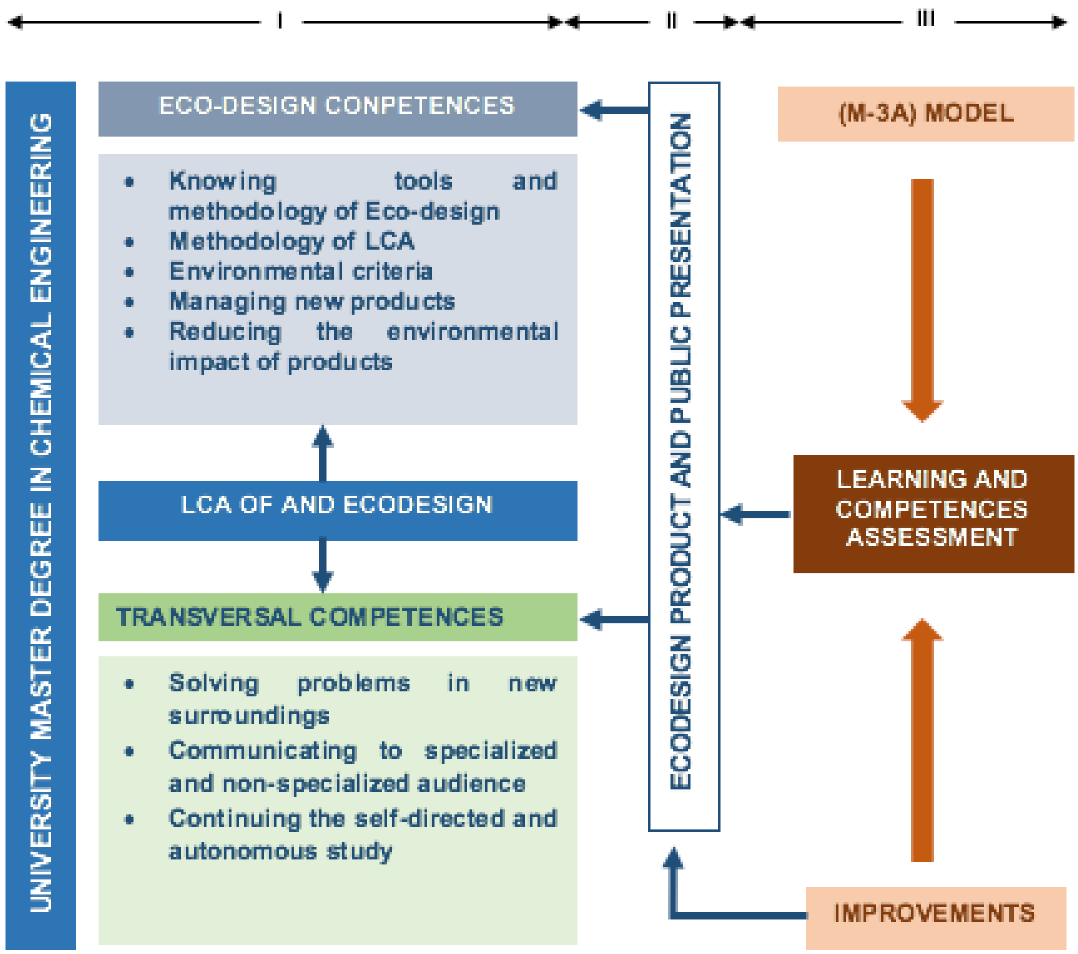

Figure 1. Conceptual diagram of the work methodology.

2.1. Context and course design

The "University Master Degree in Chemical Engineering" is an official university master degree with academic staff from the University of Cantabria (UC) and the University of the Basque Country (UPV/EHU). The first year of this master degree took place in the academic year 2014-2015. The curriculum of the master is sourced from the guiding rules released by an official resolution (8th June, 2009) of the Spanish Secretary of Universities regarding the Chemical Engineer professional (BOE, 2009).

The main target of this master is the training of professionals able to apply technical and scientific methods to propose and solve research issues, development and industrial application problems in the chemical and process engineering field. These professionals can extend later its training period to the research field as the master can be used as a bridge for the enrolment in the PhD programs of the UC and the UPV/EHU.

The target admission profile is the one corresponding to Chemical Engineering bachelors. Other students from related engineering degrees are also suitable candidates if additional ECTS credits are completed beforehand. The overall workload of the master is 90 ECTS, divided as 60 ECTS (fundamentals) and 30 (practice). This total includes the End of Master Degree Project (Figure 2). Teaching activities during the master are scheduled around 4 modules in 3 semesters (30 ECTS per semester).

Regarding the European system, the ECTS credits express the volume of learning based on the defined learning outcomes and their associated workload (EC, 2015). A typical full-time academic year has 60 ECTS credits. In each European country, national regulations define the equivalence of working loads, which belongs to the range 25 to 30 hours. The purpose is making studies and courses more transparent and thus, helping to enhance the quality of higher education. In the Spanish case, 1 ECTS credit could have an equivalence of 25 hours to 30 hours (BOE, 2003) and in particular, in the University of Cantabria the chosen equivalence is of 25 hours for 1 ECTS credit. While the implementation of the ECTS credits has been very useful for the exchange of students between European universities, there is no such a system in the USA, thus transfers vary with states and universities (Thiriet et al., 2008).

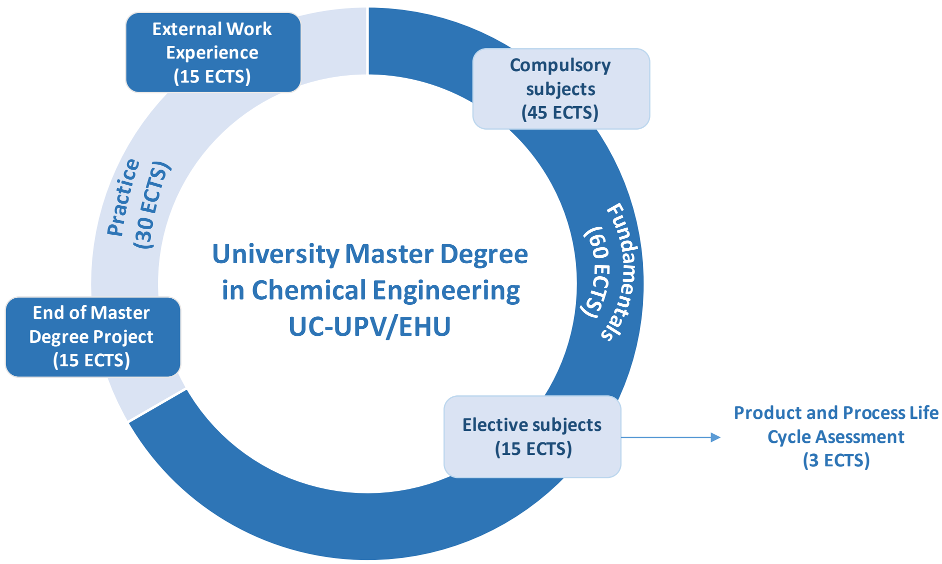

Figure 2. Structure of the University Master Degree in Chemical Engineering jointly offered by UC and UPV/EHU.

The subject Product and Process Life Cycle Assessment with a workload of 3 ECTS, is an elective course corresponding to the block “Sustainable Resource Management” of the second semester. The teaching of this course that started in 2014 is allocated to the UC. The pursued objectives of the course are threefold:

i. To understand LCA as a scientific tool which follows an international accepted guideline in order to evaluate the positive or negative effects of a product, a process or a service in the environment.

ii. To identify and calculate the environmental burdens as well the associated impacts of a product, a process or a service.

iii. To identify, know and work with different tools and LCA databases.

Because of the objectives of the course, the expected learning outcome is the students to become familiar with the LCA tool thus, they can identify the current legislation regarding the design of products and consider it in an ecodesign project.

The course is structured in three main sessions. The first session provides a brief description of the methodology and the similarities and differences of the product-LCA and process-LCA are discussed. In the second session, the students work on the ecodesign concept keeping the current regulation as a key priority element. In the final third session, practical activities including a project (the subject of this manuscript) and computer sessions are performed. As a result, the course accounts for 10 hours of fundamentals (LCA and ecodesign) and 20 hours of practice (project and computer).

A list of 10 competences is available in the teaching guide of the course. In the University of Cantabria, each competence can be completed at 3 different extension or level. Level 1 means that the competence is dealt with at its minimum level of exigency while level 3 means at its maximum. For this particular course, 3 over 10 must be fulfilled at a level 2, while the remaining 7 at a level 1. The competences for which a level 2 requirement exist are:

i. Basic knowledge for the development and/or the application of new ideas.
ii. Research and design of engineering solutions based on creativity and innovation.
iii. Putting into work the acquired knowledge and problem-solving skills in order to solve new situations.

The assessment of the final mark is the compilation of a set of individual tasks which ends up into a portfolio. No exams are envisaged in this course. Retake exams are potentially possible.

2.2. Hybrid Problem-and Project-Based Learning (PBL) life cycle assessment an Ecodesign product

Over the past few years, the idea of educating students in real-world settings has developed into a guiding vision for education in sustainability science, an explicitly problem-driven and solution-oriented academic field (Wiek et al., 2014).

In sustainability programs, the problems and projects addressed should real-world sustainability challenges. Problem-based learning centers on complex problems with no simple solution and adopts an inductive and contextual approach to hypotheses building and testing to develop a deeper understanding of such problems. Emphasis is put on critical and deep understanding and less on constructing and testing feasible solution options. On the other hand, Project-based learning models focus on developing case-specific problem understanding to create feasible solution options. A professional project-management approach provides steps and tools to structure and support students' work (Brundiers and Wiek, 2011). According to this, our model combines both approaches under a Problem-and Project-Based Learning (hereafter PPBL).

Instructors act as facilitators, but their role extends to include proactive orientation of students in the difficult process of building not only new understandings but also developing options for feasible solutions.

The PPBL was used as a central organizing principle for the course and to enable students to apply the principles of LCA of environmental impacts of a product. The project, which was assigned early in the semester and due at the end, drove all of the learning activities for the semester. The case study involved substantial group work as well as self-directed learning. According to Barrows the PPBL is a student-centered, contextualized approach to learning (Barrows, 1985), whose application to chemical engineering has previously been reported (Harris and Briscoe-Andrews, 2008). It is very important to remark that in problem-based learning, the majority of time is spent learning - by identifying what you need to know, finding out, teaching each other and then applying your new knowledge. Thus, the primary aim of the exercise is the learning, not the completion of the project. The project is simply the means to this end (Harris and Briscoe-Andrews, 2008). A key concern in the planning of the courses was the introduction of motivating factors for the students that would allow them to complete the theoretical concepts associated with LCA. For this, the ecodesign of a product was introduced in order to include a differentiating element that allows to visualize the final result of the problem with a suitable solution.

In order to maximize PPBL's potential, this work introduce the elements as following:

i. Only the objective of the ecodesign project is facilitated to the students, therefore the students must take responsibility for their own learning.
ii. Ecodesign problem is undefined and allows for free inquiry by the student.
iii. The ecodesign problem is multidisciplinary, introducing concepts along the whole supply chain of the product.
iv. The student collaboration is encouraged in both group and self-directed work.
v. Students constantly reanalyze problems.
vi. Students reflect on what they have learned from the problem.
vii. Students take part in self and peer assessment.
viii. The proposed ecodesign problems have value in the real world.
ix. Student assessments evaluate problem-solving skills.
x. PBL must be rooted in the curriculum, according to the design of the master degree.

Therefore, according to the PBBL definition, the product ecodesign project is far more than students working through problems.

2.3. Micro (Assess-Analyze-Act) (M-3A) model

In order to foster improvement, assessment scholars have emphasized the importance of examining the assessment process. These models have been widely applied in programs and institutions. However, previous studies suggested that, while most institutions have measures to assess the learning outcomes and processes to analyze the results, they are weak in the crucial stage of acting or closing the loop, that is, the process of identifying and implementing changes and then assessing the impact of the change (Schoepp and Tezcan-Una, 2017).

In this work, we propose a Micro (Assess-Analyze-Act) (M-3A) model of assessment mainly focused on closing the loop learning activities. According to this, it is necessary i) the student works and the learning outcomes assessment; ii) the analysis of the competences outcomes related to the life cycle and ecodesign concept; and iii) the proposal of individualized and collective improvements, as well as on-site action to improve results, thus closing the loop.

Figure 3 shows the Micro (Assess-Analyze-Act) (M-3A) Model proposed.

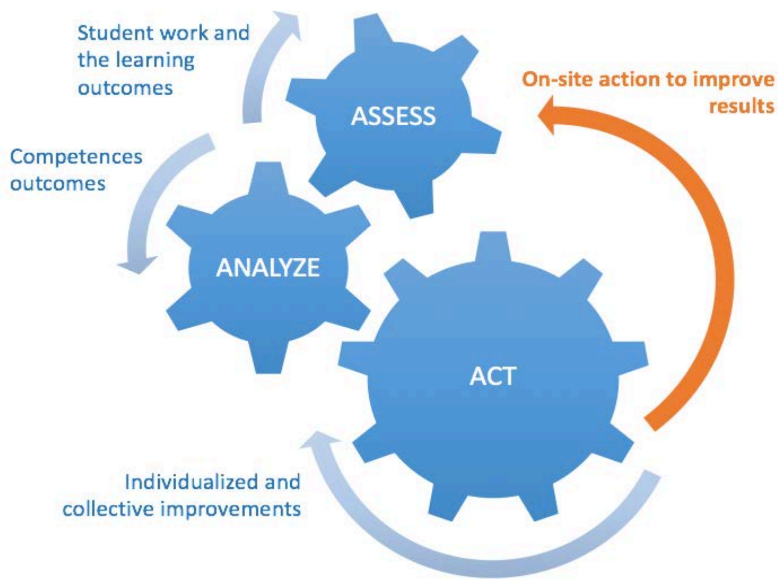

Figure 3. Micro (Assess-Analyze-Act) (M-3A) Model.

2.3 Survey performance to assess the acquisition of competences

In the course 2017-2018, an anonymous survey was sent to the enrolled 13 students, having feedback from six of them. This survey was completed a week after the end of the course.

For the sake of this study and the assessment of the acquisition of the competences two questions were formulated: question 1 asks the students to choose the competences of the

Master and of the subject that they improve thanks to the course, whereas question 2 asks about the time need to carry out the project. Supplementary material (Table S1) compiles the survey send to the students with the two previous questions.

3. Results

3.1 Student's work and evaluation of competences

The learning method of the subject was changed in the course 2016-2017. This procedure comprises in the first session of the course, the explanation of the concepts of LCA methodology and ecodesign strategies. After these theoretical classes, in a second session the students work on the ecodesign concept keeping the current regulation as a key priority element. In particular, the students apply this knowledge to conduct the ecodesign of a product. They choose this product and present their ideas by means of a poster presentation. Figure S1 in the supplementary material shows several posters from students in the course 2016/2017. The analysis of the posters allows evaluating the competences and learning outcomes related to general knowledge and life cycle assessment and ecodesign concepts. A list of 10 competences (Table 1), available in the teaching guide of the course, was assessed denoting that only 50% of them were acquired in this stage. The results show that the students need to improve the capacity to determine the hot spots of the processes using LCA and to identify the most environmental friendly product. Another point is to increase their knowledge about ecological labelling, which will help them to communicate to the users the minor or greater environmental goodness of the products. This is a key competence that industry calls to be improved in their future professionals. In fact, the importance of communication skills has reinvigorated the communication-across-the-curriculum movement (Dannels et al., 2003)

Table 1. Assessment of the acquisition of competencies in the intermediate and final evaluation

	Competences	Intermediate evaluation	Final evaluation
1	Integrate knowledge and to be able face to make judgements based on limited information and their reflections	✓	✓
2	Understand the importance of Ecodesign for the achievement of Sustainable Development and of considering the complete life cycle of the products designed when evaluating their environmental impact	✓	✓
3	Know different methods and tools of Ecodesign	✓	✓
4	Put in practice a methodology of Ecodesign	✓	✓
5	Learn the methodology to perform a life cycle assessment	✓	✓
6	Adjust environmental criteria for new products	✗	✓
7	Manage new products: design focusing on the user	✗	✓
8	Capacity to know the factors on which to act to reduce the environmental impact of products	✗	✓
9	Capacity for the identification of those products whose total impact on the environment, throughout its life cycle, is lower	✗	✓
10	Knowledge of the existing systems to communicate to the users of the products the minor or greater environmental goodness of the same ones, through the systems of ecological labelling	✗	✓

Based on this intermediate evaluation, the students are proposed in the third session to carry out individualized and collective improvements and to implement these measures in the development of an ecodesigned product. Figure S2 shows some of the products that were exhibited in the hall of the University in an open public session, where all the academic community was invited to assist and participate. The students might communicate to the public the ecodesign strategies implemented in the development of a new product. The evaluation of this third session determined that finally the 100% of the competences were acquired. Therefore, the application of the M-3A Model demonstrated overall learning strengths and weaknesses, while also pointing to specific needs of individual units of ecodesign stages, p closing the loop of learning activities.

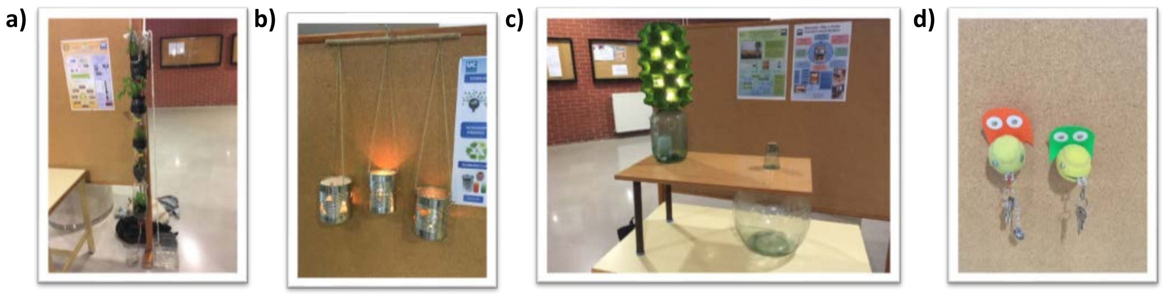

Figure 4. Ecodesigned products a) vertical suspended garden, b) lantern using recycled canned food, c) lamp made with egg box and d) key-ring recycling tennis balls.

3.2 Student’s interaction and marks Student’s feedback indicated that examples of the type shown above have helped them to understand the principles of LCA, particularly in their first year of the chemical engineering program. The students felt the approach has allowed them in the first instance to utilize their analytical skills in quantifying a situation before applying other subjective measures, i.e societal impact or consumer acceptance, that engineers often have difficulty in assessing.

The challenge of introducing elements of ecodesign associated with the qualitative analysis of the life cycle in the classroom is to promote the student's discussion in a way that complements the quantitative analysis of the previous courses.

The public discussion of the results has introduced a satisfactory element for students and instructors. As studied by Evans et al., while a student may have a strong personal opinion on a particular topic, they often remain silent when asked a direct question. The reasons for silence may vary, but this is usually because an individual is concerned that they may be asked to justify their choice for the class (Evans et al., 2008). To overcome this reticence, the particular knowledge of the problem introduces an element of trust. The advantages of several cases studies are obvious: it involves each student both personally and collectively; a student can justify his response against his peers; and the instructor can use the answers to promote the debate on subjects in which there is a diversity of points of view.

The proposed methodology through a combination of quantitative analysis and qualitative preference, highlighted to students that an engineering approach to sustainability went well beyond simply performing a set of calculations. In addition, the feedback from the students has been overall positive. There is a gradual realization from students that they can apply their own interpretations as long as they objectively support their assumptions. They also begin to appreciate the views of others.

The interest with which students answered to these ideas, and the responsibility they demonstrated in taking control of their own learning were both positive outcomes. Student feedback in the form of the confidential paper-based survey managed by the University's Quality Unity was positive and demonstrated the impact of the teaching and learning style on student outcomes. In particular, the overall student satisfaction with the teaching and learning activities had a mean score of 3.71 (out of 5) in the academic course 2016-2017. Individual students commented that the 'think outside the box' nature of the unit was a highlight they would like to see incorporated more widely into their degree. Regarding the marks (Figure 5), all the students passed the subject in the first call in the courses 2014-2015, 2015-2016, 2016-2017 and 2017-2018. On average in this period, 35.5 % and 43% of the students get an outstanding (10-9) and a mention (7-8), respectively. In the course 2015-2016 there was a decrease in the marks, having an increasing trend in the next courses when the M3A method was applied, reaching in the course 2017-2018 a maximum value of 9.15.

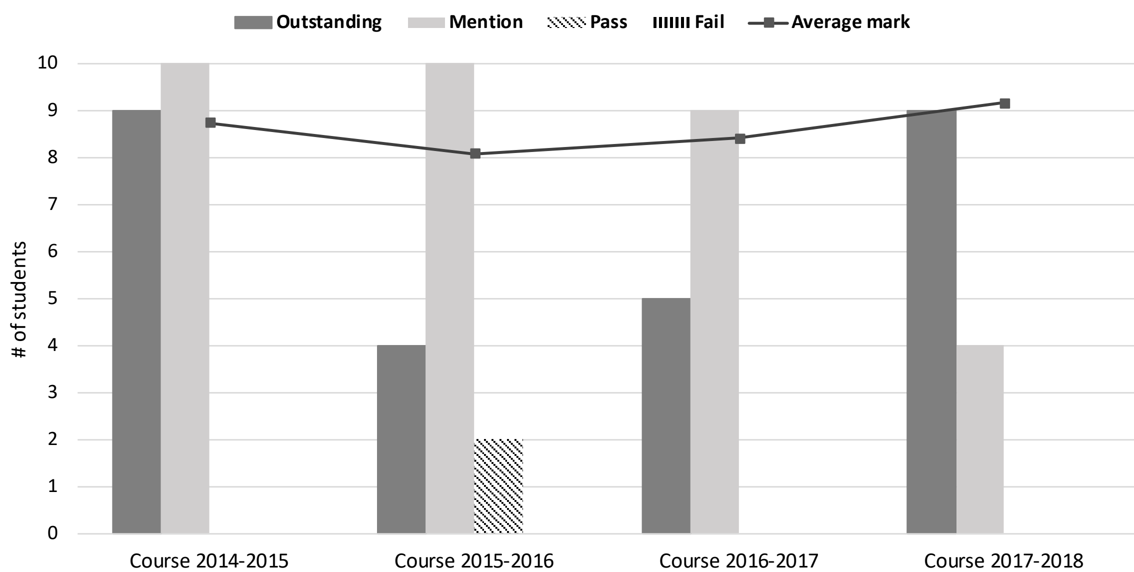

Figure 5. Comparison of marks for the academic courses 2014-2015, 2015-2016, 2016-2017 and 2017-2018. Outstanding (9-19), mention (7-8), pass (5-6), fail (0-4).

3.3 Results of the performance survey

This section provides the answers of the two questions of the survey conducted in the course 2017-2018. Figure 6 displays the number of times that the master and subject competences have been chosen by the surveyed student as a competence he or she has improved thanks to the course within the master programme. Competence that did not received any answer were excluded from Figure 6.

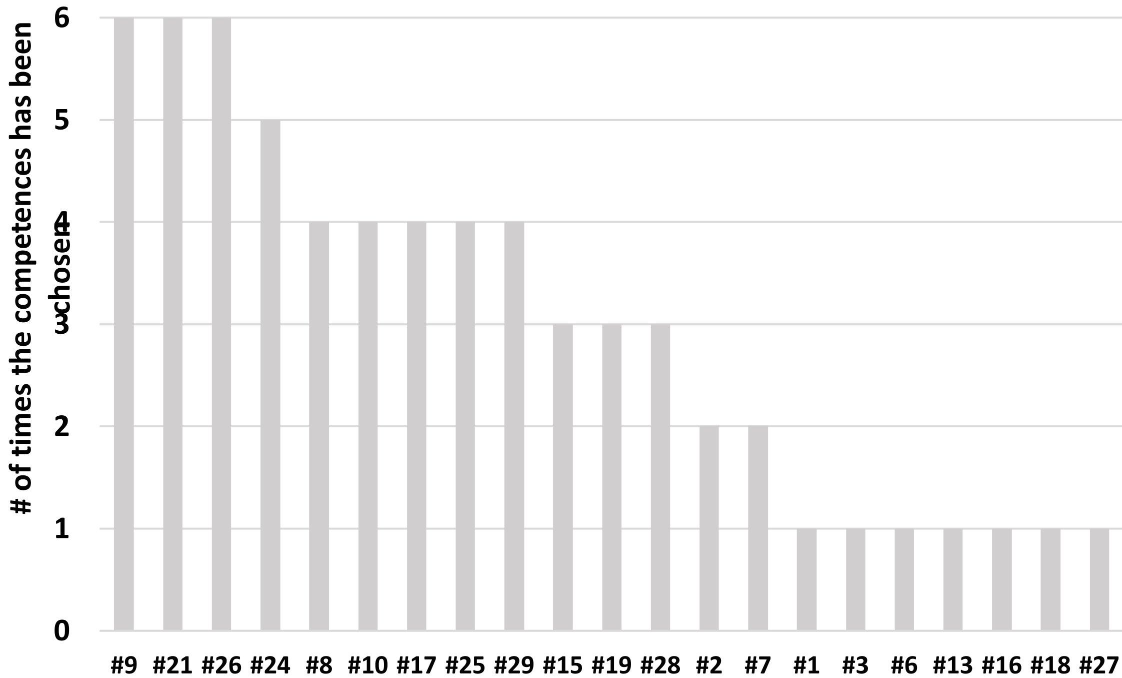

Figure 6. Number of times that the chosen competence by the master student has improved due to the course.

As shown in Figure 7, there are 21 competences that have been selected by the students as relevant. They have highlighted 4 competences preferentially: #9 (teamwork), #21 (creativity); #26 (relevance of environmental issues); and #24 (initiative and entrepreneurship). It is worthy to highlight the fact that the competence #26 reached one of the top positions, which is suggested to be related to the overall concerns on environmental issues by younger members of the modern society.

Surprisingly, even if the number of completed surveys was low (due to the small number of students in the course), no one answered that it took much more or much less time than expected. Consequently, the workload was nicely adjusted, which is a driver to continue with the development of the current approach.

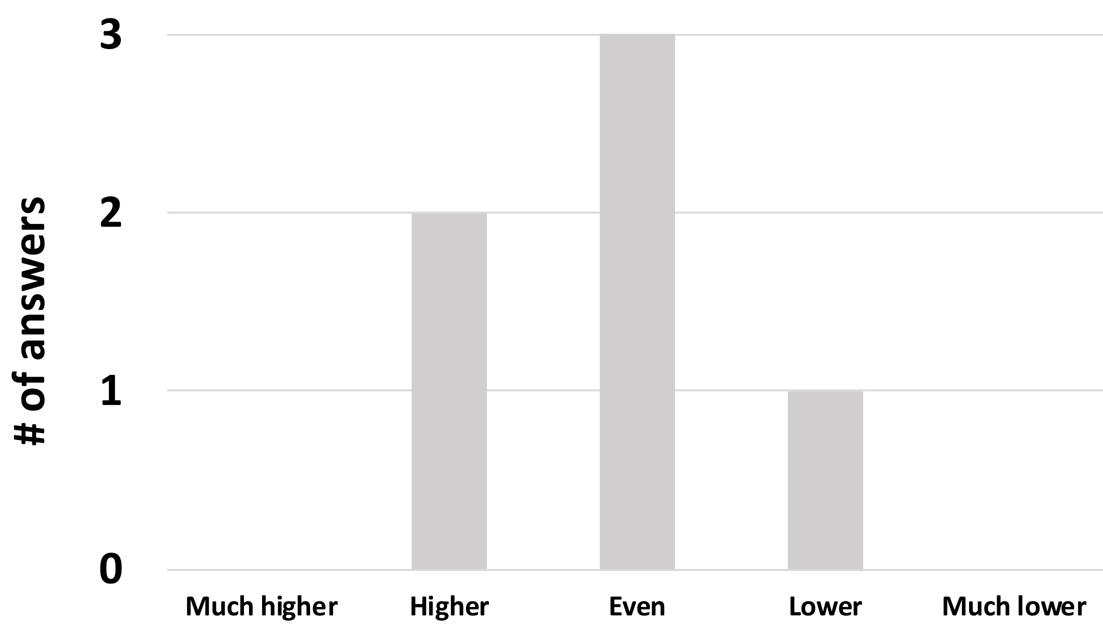

Figure 7. Number of answers regarding the number of hours that the course requested to pass it adequately versus their initial expectations regarding that number.

4. Conclusions

The chemical engineering students must be comfortable taking proprietorship of their education in order to they become successful and efficient life-long learners. Taking into account the complex and multidisciplinary problem-solving nature of the chemical engineering profession, PPBL is an essential tool to train future chemical engineers for the workplace.

This course experience of master's degree in green chemical engineering used a real-world' problem as stimuli for learning. The ecodesign case study trough the proposed methodology demonstrated overall learning strengths and disadvantages, while also pointing to specific needs, from a technical point of view, of the life cycle assessment knowledge and ecodesign stages.

The experience from the course at Cantabria University was that this learning thinking was a significant challenge for many students who had not previously been exposed to it. There were also challenges during the course: the approach requires skilled and knowledgeable instructors, as well as a set of appropriate case studies in order to show examples of projects. We solved these problems by using previous works of PhD students who were intimately familiar with the material being studied through their own research work. Individual students commented that the PBBL nature of the experience was an interesting know-how they would like to see incorporated more widely into their degree. However, the results offer insights into where and how to improve. In addition, these problems help to integrate and organize learned information in ways that will improve recollection and application of knowledge to future problems.

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