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Learning by doing using the Life Cycle Assessment tool: LCA projects in collaboration with industries

Marta Rumayor[a,*], María Margallo[a], Javier Pinedo[b], Jonathan Albo[a]

[a] Universidad de Cantabria, Departamento de Ingenierías Química y Biomolecular, Av. Los Castros s/n, Santander, Spain
[b] APRIA Systems, Parque Empresarial de Morero, Parcela P.2-12 - Nave 1 Puerta, Guarnizo, Cantabria 39611, Spain

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ABSTRACT

Active learning, also called "learning by doing" (LbD), has resulted in positive learning outcomes in several higher education degrees. This paper describes an LbD experience within Chemical Engineering education aiming to enhance learning and transferable competencies using a Life Cycle Assessment course as a vehicle. This compulsory course belongs to the European Project Semester (EPS) program taught in the fourth year of the Chemical Engineering Degree at the University of Cantabria. From the beginning, the activity has targeted LCA practice with a strong emphasis on performance and its application as a decision-making tool in real case studies through close collaboration with regional companies. Working in partnership with industrial companies has favoured a win-win-win situation as students could apply knowledge as future LCA specialists. In contrast, companies gained valuable insights to improve their environmental performance, and lecturers enhanced their industrial networks. A public session carried out at the end of the activity created an enriching debate on subjects from a diversity of points of view (e.g., the selection of impact categories, the proposed improvements for environmental impact reduction, etc.). According to the lecturers, the competencies acquired by students through this LbD experience in life cycle assessment have notably evolved, demonstrating not only an enhanced understanding of environmental impacts across a product life cycle but also a significant improvement in critical thinking, team collaboration, and practical problem-solving skills, thereby bridging the gap between theoretical knowledge and its application in real-world scenarios. This is in line with the student’s perception that considered, such as "problem resolution", "capacity for analysing" and synthesis and "capacity for information" management. These are essential not only for future LCA practitioners but for chemical engineers.

1. Introduction

Despite chemical engineering students being traditionally well-trained in theory, most feel significant obstacles when applying their knowledge in open-ended real case studies (Rugarcia et al., 2000). A noticeable disconnect between the skills of trained engineers and the qualities desired by society began to surface. This discussion expanded beyond just the realm of chemical engineering and extended to all engineering disciplines. It delved deeper into issues such as the capacity of future professionals to engage effectively in social contexts and address the increasingly intricate and interdisciplinary global challenges of our time such as sustainability, resilience, etc. (Broo et al., 2022). Undoubtedly, the more complex their challenges are, the more critical the transferable competencies acquired during learning are. Engineering education has to be adapted following future industry requirements, improving those abilities that engineers will face when leaving the academic environment (Yoshino et al., 2020). Furthermore, it has been projected that the future of the workforce needs social and transferable competencies (Martin, 2018), especially leadership and information management, that are projected to increase by 24 percent (Bughin et al., 2018).

Grant and Dickson (2006) outlined the development of transferable competencies within the field of chemical engineering after perceiving a ‘skills deficit’ upon entering employment. They pinpointed several key transferable skills vital for chemical engineering graduates, including communication, teamwork, problem-solving, numeracy, IT proficiency, and the ability to engage in self- learning. These skills align with those recognised by the World Chemical Engineering Council (World Chemical Engineering Council, 2004), which drew upon feedback from chemical engineering graduates and employers, primarily gathered

* Corresponding author.
E-mail address: rumayorm@unican.es (M. Rumayor).

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through questionnaires. More recently, Fletcher et al. (2017) have appointed that these transferable skills hold significant importance for students and graduates seeking to enhance their employability prospects in the field of chemical engineering.

Developing competencies is highly effective when using active learning, an engaging, hands-on method for acquiring knowledge and skills. Active learning fosters active participation among learners, stimulating a deeper understanding of the subject matter and enhancing information retention. Several strategies to implement active learning into chemical engineering curricula using activities and evaluation tools have been proposed in the latest decade (Karjanto, 2022). Glassey and Haile (2012) suggested a concentrated strategy based on a week-long module that introduces fundamentals of chemical engineering in the first year and then, students can solve several industrially relevant case studies with significant societal impact using enquiry-based learning (EBL). Allen and Shonnard (2012) emphasized the necessity of acquiring knowledge outside the chemical engineering discipline through collaboration with experts from different fields to achieve sustainable designs. Othman et al. (2012) introduced the so-called sustainability assessment and selection (SAS) concept into the Computer Aided Plant Design (CAPD) course. The framework of their activity consisted of a one-day lecture and a practical example in which students had to select sustainable process design options. Montañés et al. (2012) introduced the sustainability concept in chemical engineering education through an environmental management system laboratory work. Feijoo et al. (2018) proposed a Gamestorming methodology to assess and select sustainable alternatives within the Conceptual Design of Products and Processes, enhancing students' creativity. Margallo et al. (2019) applied a Micro (Assess-Analyze-Act) (M-3A) model of assessment to an ecodesign case study that not only promoted sustainability and ecodesign skills, but also transversal competencies (e.g. solving new problems, communication, having critical thinking, etc.). Most of these strategies are intended to enhance students' initiative, versatility, creativity and innovation as they are based on methodologies and ways of approaching the teaching-learning binomial.

Chemical engineers possess a distinct advantage in assuming technical sustainability positions across various industries, being at the forefront of sustainable innovation and working to create a more environmentally friendly and sustainable future through their technical expertise and problem-solving abilities. Over time, the widely used term sustainability criteria in process engineering was primarily centred around environmental considerations that engineers must face. However, a broader range of attributes are required not only to handle the uncertainties of complex systems, but also to adopt interdisciplinary and transdisciplinary approaches. These attributes include communication, collaborative teamwork, critical thinking, and impactful stakeholder engagement (Brundiers and Wiek, 2017). In the coming years, engineers equipped with the skills to develop sustainable processes will be called upon to design strategies that maximise circular economy, reducing energy demand, natural resource consumption, and environmental emissions (Harris and Briscoe-Andrews, 2008). However, improving the competencies that boost decision-making competencies to deal with real industrial environmental problems is still an education challenge. To address this gap, the research question of the present study is: what are the opportunities to boost transferable competencies when implementing active learning in collaboration with industries in a life cycle assessment course?

Life Cycle Assessment (LCA) courses have traditionally been taught conservatively (Viere et al., 2021). Lecturing is the most common way of communicating essential LCA content to students, including brief exercises and encouraging discussions. However, due to the rapid advancements in science and technology, engineering and universities have been pushed to find more effective strategies to instruct traditional technical knowledge with relevant competencies to the student community. Indeed, the dynamic engagement of students during class may improve how they learn effectively (Mazur, 2009) In the latest years, student-centred learning activities are gaining importance in higher education, such as Learning-by-Doing (LbD) (Dominguez-Ramos et al., 2019) and Project-Based Learning (PBL) (Rajan et al., 2019). Teaching approaches have changed even faster due to the COVID-19 pandemic, which has already involved a worldwide shift from classroom teaching to online teaching (García-Morales et al., 2021). Many learning strategies can be used to develop several skills in graduating engineers, but the LbD approach is one of the most requested pedagogical methods in engineering education. Engineers should have the proper skills in "Doing Something Physical", which includes all cognitive domains of learning (Krathwohl, 2002). These competencies within the cognitive domain include recognising, interpreting, comparing, implementing, organising, critiquing, planning, and producing. The active LbD strategy involves students more directly in the learning process than conventional methods. A well-known example of LbD in the Chemical Engineering field is the Chem-E-Car Competition® (American Institute of Chemical Engineers, 2018) that boosted the development of transferable competencies, such as team building, leadership and communication. These competencies have been already listed in the "Recommendations for Chemical Engineering Education in a Bologna Three Cycle Degree System" document (European Federation of Chemical Engineering, 2010). Despite "Doing Something Physical" can be easily applied in Chemical Engineering, there are areas of knowledge such as LCA, which cannot always be associated with constructing physical prototypes due to their intrinsic characteristics.

This study evaluates the competencies acquired through a LbD experience using the practical content of the Life Cycle Assessment course of the fourth year Bachelor's Degree in Chemical Engineering at the University of Cantabria (UC) as a vehicle. Because this activity is conducted closely with regional companies, our primary purpose is transforming students into LCA practitioners. Proper implementation of LCA in undergraduate courses could strengthen the ethical and humanitarian values of future business communities. Thus, applying an appropriate pedagogy is the key to student engagement in the learning process, which will lead to applying LCA concepts to solve technical problems. Although LCA is taught in many higher education degrees worldwide (Burnley et al., 2019), there are very few reported experiences with industrial partners. Cosme et al. (2019) conducted an experience at Master of Science (MSc) level regarding teaching LCA in collaboration with industries. They appointed a higher engagement of students through this experience, which provided them with several sustainability-related skills. A similar experience was conducted by Piekarski et al. (2019) for students of Industrial Engineering at the Federal University of Technology – Parana (UTFPR), reaching a win-win-win approach between lecturers, students, and industries. Our study aims to complement those experiences by applying the learning methodology for students of Chemical Engineering Degree and evaluating in detail the acquisition of competencies that were not shown in the previous experiences.

The present study explores the possibilities for enhancing professional competencies by incorporating active learning alongside industry partnerships within a life cycle assessment course. Through the proposed experience, students are expected to obtain a life cycle inventory using data from real companies and present an LCA report following the ISO14040/14044 standards (ISO 2006a, 2006b). The novelty of this LbD methodology, compared with the traditional practical module, is the replacement of obtaining data from easily accessible conventional sources, such as books or scientific articles, by carrying out inventories from a real company that may boost decision-making, creativity, and leadership, among others. In addition, students present the LCA report in a public event with the company representatives instead of the conventional defence of results to the lecturers. The results obtained in this study demonstrate how this experience boosts a win-win-win situation, enhancing the student's engagement and the acquisition of professional competencies. In contrast, companies obtain valuable insights and lecturers reinforce their network with industries.

2. Methodology

2.1. Context of the course

The methodology of LbD has been introduced as a complement to the practical content of the Life Cycle Assessment course taught in the fourth year of the Chemical Engineering Degree at UC, located in Northern Spain. The Life Cycle Assessment course belongs to the European Project Semester (EPS) program, which several European universities offer (European Project Semester, 2014) (Fig. 1). This program is commonly orientated to engineering students who have completed at least two courses, although they can also feed on students from other disciplines. The program has a maximum number of students of 10. The access is done by average grade and students must have a B2 level of English. The courses included in EPS are compulsory and involve elaborating projects, so they are commonly based on learning using PBL methodology. EPS at UC started to be taught in 2013/2014 and it has 30 ECTS structured in two sections: 18 ECTS distributed in three elective subjects taught in English and 12 ECTS corresponding to the Final Degree Project, also supervised, and defended in a foreign language (Rivero et al., 2014). Students of EPS commonly work in teams and take an active role in their learning process while developing communication skills and interpersonal relationships.

The Life Cycle Assessment course (6 ECTS) has been traditionally taught using 15 hours for basic principles on LCA, whereas a greater percentage of hours is dedicated to practical work (45 hours). The learning outcomes are found in Table 1.

The first part of the course provides students with knowledge about LCA principles according to ISO 1440 and 14044 Standards (ISO 2006a, 2006b). Furthermore, the practical sessions have been traditionally divided into two phases. Firstly, students solve brief exercises (tasks 1–4) regarding LCA methodology (Fig. 1) and complete an LCA case study. During these sessions, students analyse the environmental impacts of the collected data using LCA software. The practical content aims to develop skills and insights across LCA steps, such as goal and scope definition, life cycle inventory modelling, data quality assessment, choice of impact assessment categories, interpretation and uncertainty assessment. This part is accomplished by working with LCA software and databases. The commercial GaBi Academy software from Sphera (Sphera. 2022) was used until the course 2019–2020, applying the GaBi Professional database. Since the 2020–2021 course, the commercial software has been substituted by the open-source openLCA (GreenDelta, 2022), allowing the application of worldwide LCA databases, such as Ecoinvent, Agrybalise, and GaBi Professional. In addition, the learning method of the first part of this subject was changed in the course 2020–2021 carrying out an international exchange between lecturers from UC and Sami Shamoon College of Engineering (Israel) under a Collaborative Online International (COIL) project in the Degree in Chemical Engineering at UC (Margallo et al., 2022). This course aims to promote the improvement of several competencies, which are found in the syllabus of the course (Table 2).

Table 1
Learning outcomes of the Life Cycle Assessment course.

LO.1	Applying the concept of Life Cycle Thinking
LO.2	Performing a Life Cycle Assessment study: goal and scope definition, life cycle inventory, impact assessment and interpretation
LO.3	Using an open-source Life Cycle Assessment software

2.2. Design and content of the LbD activity

This activity was carried out by 10 students (the maximum number of students in the EPS program) divided into 5 groups of 2 students. The work was developed over 3 months after the company contact. In addition to the tasks performed at each stage and the oral presentation, the students fulfilled two surveys. Fig. 2 displays the outline of the objectives and tasks that students had to complete during the course highlighting the practical activity proposed during the course 2021–2022, continued in 2022–2023, and is still working in the course 2023–2024. The methodology was planned to promote their participation in the practical content of the course through a student-centred strategy of LbD replacing conventional case studies prepared by the lecturers. We hypothesised that dealing with the expected challenges found during the LCA application to real-case studies would engage students during the course. On the one hand, university-industry collaboration would improve students' learning by providing a vehicle for synthesising knowledge from the fields of teachers' professional learning. On the other hand, students would have to tackle common challenges for LCA practitioners, for example, the lack of data and uncertainty. Facing these challenges might result in a clear improvement in students' decision-making. In this activity, students analysed the impacts of their decisions through cooperative and participative teamwork in an iterative way.

Undoubtedly, applying the LCA tool to real-life industrial case studies would engage cognitive, affective, and behavioural learning. The final purpose of this activity was to enrich the learning experience for students by promoting several professional competencies that prepare them to meet the current competencies demanded by industries.

The stages of this activity were:

i. During the first two weeks of the course (W1-W2), lecturers contacted chemical industries related to the production of basic materials, chemicals and food. These companies had to preferably be placed in the region of Cantabria (Northern Spain) to facilitate a close collaboration during the activity. The representative persons would be available to solve any questions from the students up to the end of the activity (W16).
ii. During the fourth week of the course, students were divided into five groups, each of which was responsible for one of the case studies. During one month (W5-W8), they should analyse the case

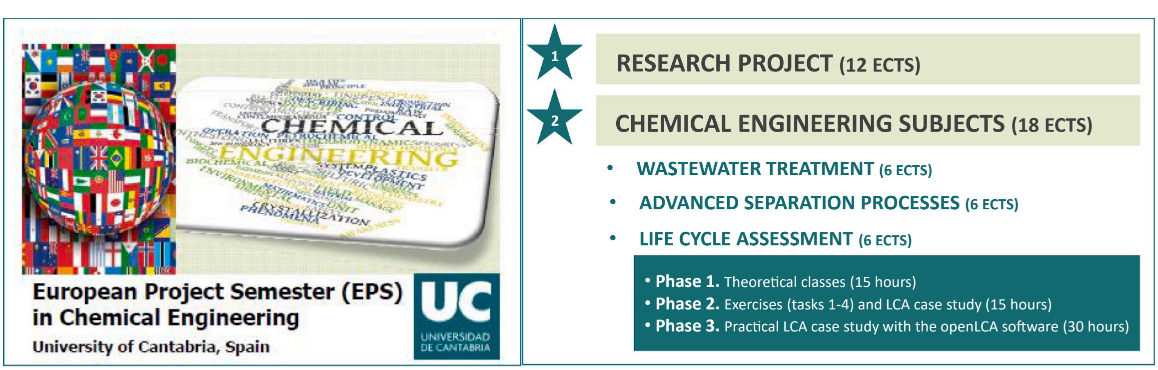


Fig. 1. Structure of the EPS program and the Life Cycle Assessment course.

Table 2
Main competencies worked during the Life Cycle Assessment course.

Basic competencies
Sensitivity towards social and environmental issues
Knowledge of other cultures and other students in an international environment
Specific competencies
Ability to apply chemical engineering knowledge in practice
Ability to organise and plan the procedure
Problem resolution
Transversal competencies
Decision making
Teamwork
Intercultural skills

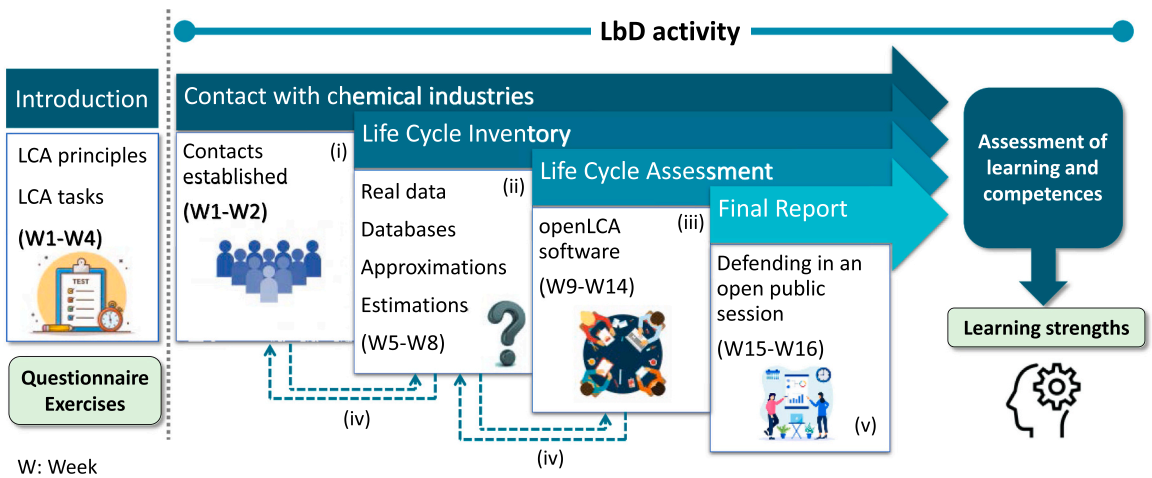


Fig. 2. Conceptual diagram of the work methodology of the course.

study and establish the goal and scope. Then, they were able to work on the life cycle inventory (LCI) collection considering the data uncertainty and selecting the proper LCA method. In this stage, students could use the company information available, as well as the LCA databases or make approximations. During the first session, lecturers recommended to follow a hierarchy. This consisted of 1) consulting the information provided by the industry; 2) consulting databases (GaBi Professional); and finally 3) making approximations such as mass and energy balances. This stage was expected as the most time-consuming since data have to be verified in order to obtain a high-quality and representative LCI. The duration was fixed as four weeks. Since this activity was conducted in an iterative way, students could return to this stage at any time making the necessary improvements.

iii. The next six weeks (W9-W14), students introduced the life cycle inventories in the openLCA software to analyse the impact assessment categories of the selected LCIA method. They carried out an attributional LCA from a cradle-to-gate perspective. In this stage, they could determine the most relevant environmental impacts of the companies. Students could compile the LCA impacts in an iterative way after any improvements in the LCIs.

iv. During the overall duration of this activity, students could contact the company contact person if necessary to solve any questions or missing data. It was established a panel of experts from the companies, lecturers, and students, helping the data collection, assumptions and calculation of the LCIs. Students were able to improve their LCIs (stage ii) during the duration of the activity with new data obtained through the contacts from industry (stage i) and the advice given by lecturers in a weekly session.

v. During the last two weeks, students prepared a final report, which was planned to be evaluated by the lecturer team and defended in a public session along with the company contacts involved. Students received then feedback to make the adjustments and corrections needed while valuable information about sustainability was received by industries.

The first three stages were iterative according to the LCA methodology; after obtaining the relevant impacts, they could contact the industry representative, improve the estimations, consult alternative databases and then compile the results at any time. The activity has a single deliverable at the end of the activity (week 16) together with an oral defence. During the development of this activity, lecturers made interventions in a weekly session to assist and evaluate the progress of the proposed actions according to the LCA procedure. The final presentation should last about 15 minutes and it had to contain: i) a detailed description of the company chemical processes involved; ii) the goal and scope definition to analyse the environmental performance, including a complete flow diagram and a description of the system boundaries and functional unit selected; iii) the procedure to obtain the LCI and data uncertainty (e.g. real data, estimations, approximations, etc.); iv) the selection of impact categories and impact method and reasons to choose them and; vi) the conclusions resulting from the assessment and the proposed actions to improve the environmental performance of the company that would assist their decision-making.

Lecturers promoted a final discussion about possible improvements in the processes/technologies applied in the industries and the origin and reasons for the environmental impacts. All team members of the groups were expected to make a significant contribution to the project.

For the academic evaluation of the course, the knowledge of LCA principles was verified during the first month. This evaluation was conducted traditionally through a multiple-answer questionnaire (40 % of the final mark) and LCA exercises (10 % of the final mark). Then, the LbD activity was evaluated through a rubric that evaluated the teamwork during weekly sessions (30 %), the final report and oral defence

(50 %), and a set of key competencies (20 %). Regarding the report and oral defence, report quality entailed 40 % while oral defence criteria accounted for 60 % of this part. The criteria included can be found in the Supporting Information (Tables S2-S4). Briefly, the rubric of the weekly sessions was made to evaluate the acquisition of main LCA concepts, the ability to build up the LCI and the use of the LCA software. The evaluation of the report and oral defence considered the report's quality and organisation, time management during the oral defence, student' confidence to communicate and their ability to answer questions. Finally, global competencies were observed and evaluated by the lecturers together with the LCA learning outcomes through the competencies rubric, which includes those within teamwork, communication, and related problem-solving. If the mark of the project was below the minimum mark (5.00), the student could pass a retake exam. An additional retake exam was possible on the date established by the School of Industrial Engineering and Telecommunications board.

Because this activity involved real data collection. Students were conscious of the ethical considerations. The best practices to follow when collaborating with industry may include:

1. Communicate the goal of the data collection to the industrial representative and how data is going to be used.
2. Address any legal requirements with the industrial representative including the non-disclosure agreement.
3. Ensure any legal requirements for handling sensitive data and maintain confidentiality.
4. Follow a detail data collection plan during the timeline of the activity (a maximum of one contact every two weeks might be enough to conduct this activity).
5. Include the data collection procedure or estimations in the final report.
6. Share the results with the representatives.

Through an initial survey, they were asked about their competencies before the course on a five-point scale (being 1 slightly acquired and 5 fully acquired according to them). Note that the surveys were based on self-awareness, and therefore students identify competencies where they feel less confident or skilled. For this reason, at the end of the course, they fulfilled another survey with their personal opinions about those competencies that progress the most. This final survey includes also their impressions about time effort and any other suggestions to improve (Table 3). The surveys were anonymous and submitted in an electronic form. The competencies that were improved after the course were classified as "strong" and "weak" according to the authors. "Weak" would mean that less than 50 % of students considered improving their competency, whereas "strong" would mean that more than 51 % selected to have improved their competency.

3. Results and discussion

Two Learning-by-Doing (LbD) experiences were implemented satisfactorily in the Chemical Engineering Degree at UC improving the acquisition of several competencies. Dominguez-Ramos et al. (2019) identified "Problem-solving" and "Adaptation to new situations" as key competencies in the Chem-E-Car Competition® experience. Margallo et al. (2019) highlighted the acquisition of competencies including teamwork, creativity, the relevance of environmental issues and initiative and entrepreneurship. The previous experiences lay the foundations of the current study; since we have used the Life Cycle Assessment course as a vehicle to improve the competencies acquisition through this LbD experience and analysing the learning benefits of collaborating with companies as well as the student outcomes.

3.1. Activity development and evaluation

During the first two weeks of the course, lecturers established contacts with industries of the region. It reached a success rate of 60 %; five companies were contacted and three of them confirmed their availability to participate in this experience. Lecturers informed about the time of the activity at the beginning of the course and the students were divided into 5 groups on week 5. Therefore, each group started to work on a real case study following the LCA ISOs. From the very beginning, they dealt with the main challenge found by LCA practitioners, which is the lack of data and uncertainty (Laurent et al., 2020). Because the proposed activity was based on open-ended case studies, students had to make various decisions along the way, and therefore, they had their perception about the time-effort to complete the overall activity. During the first month of the activity (week 5–8), they focused on the goal and scope definition, as well as on the life cycle inventory construction, discussing the status of the task and difficulties in weekly sessions with lecturers that maintained a supportive environment encouraging exploration, learning from mistakes and keeping the contact with industry representatives. During the classroom sessions, students were encouraged to follow the hierarchy provided and do the energy and materials balance when necessary to achieve as much detail as possible. Lecturers provided feedback to avoid abandonment, promoting critical thinking through collective questions related to the main assumptions taken to solve the lack of data. Despite having different case studies, teams could collaborate among them with ideas to solve the possible gaps and challenges. As previously mentioned, they conducted an attributional LCA from a cradle-to-gate perspective. Then, the utilisation, transportation and end-of-life stages were out of their studies.

Despite the fact students could contact the company representative person to solve any questions, a hotspot when working with real companies might be to maintain regular and consistent communication to prevent misunderstandings and promote engagement and positive relationships. In this sense, each group had to inform representatives of the defined objective at the beginning of the activity. Another hotspot was ensuring a successful data collection was to maintain effective communication and ethical conduct according to the guidelines shown in the previous section. Through this activity, students were conscious of some practices that they must care about when using real data. In some cases, students overcame the gap of lack of data by consulting the public

Table 3
Survey of the perceived skills improved after the activity.

1. Select the interpersonal skills you think have improved

_Capacity for analysis and synthesis (#1)	_Ability to apply knowledge in practice (#15)
_Ability to organise and plan (#2)	_Ability to learn autonomously (#16)
_Oral and written communication (#3)	_Adaptation to new situations (#17)
_Knowledge of a foreign language (#4)	_Ability to work autonomously (#18)
_Knowledge of software in the area (#5)	_Creativity (#19)
_Information management capacity (#6)	_Leadership (#20)
_Problem resolution (#7)	_Knowledge of other cultures and other students in an international (#21)
_Decision making (#8)	_Motivation for quality (#22)
_Teamwork (#9)	_Sensitivity towards environmental issues (#23)
_Working in an interdisciplinary team (#10)	_Research skills (#24)
_Working in an international context (#11)	_Design and project management (#25)
_Interpersonal relationships (#12)	_Achievement motivation (#26)
_Ability to communicate with experts from other areas (#13)	
_Recognition of diversity and multiculturalism (#14)	

2. The time-effort to solve this activity was

_Much higher than expected
_Higher than expected
_Same as expected
_Lower than expected
_Much lower than expected

Integrated Environmental Licence (MAPA, 2016) of the companies. The Integrated Environmental License provides a complete overview of the process and information about the consumption of resources and the sources of pollution to air and water. Moreover, they could look up air and water emissions and waste generation in the Spanish Pollutant Release and Transfer Register (PRTR) and, when needed, they carried out estimations and approximations when needed under the supervision of the lecturer team. During the life cycle inventory construction process, they were aware of the uncertainties involved that, in any case, should be included in the final report.

During the second stage (week 9–14), students got familiar with the openLCA software. At this stage, lecturers introduce the software providing simple examples of industrial processes with accessible data. Students introduced the inventories from the previous stage creating the needed processes and flows when needed. During the last two weeks of this stage, they calculated the impact categories with the selected impact assessment method. At this stage, students were able to identify the hotspots of the processes and propose improvement measures and recommendations that would be reported to the companies.

Students that worked as LCA practitioners considered the uncertainties that could involve their decisions and were aware of how these could influence the associated results and conclusions. They presented the results in front of both industry contacts and the lecturer team who used a rubric to evaluate this activity. The availability of the industry representative to come in a fixed-day session could be a hotspot when working with industries, however, we can highlight that the public session was conducted satisfactorily. Not only for students but also for lecturers who could promote the debate on subjects from a diversity of points of view (e.g. selection of impact categories, the proposed improvements for environmental impact reduction, etc.). In fact, the representatives who assisted the final session promoted quite an enriching debate sharing their actions towards sustainability. Lecturers could follow the progress of the students during weekly sessions, and evaluate the understanding of concepts, ability to build up LCI, and the skills to use the LCA software the average grade in the 2021–2022 course was 7.40 increasing in the latest course (2022–2023) to 8.00 (Table S5, Supporting Information).

A greater engagement of students has been noticed during the realisation of the tasks proposed when using a real case study that directly involves companies from the region (food, basic materials, chemicals, etc.) in comparison with the traditional approach of teaching LCA concepts and applying them to prepared exercises. The analysis of the oral presentations, as well as the final report, allowed us to evaluate the learning outcomes related to sustainability and LCA concepts solidly. The individual contribution of each student to the group project was checked in the oral defence of the project and during the practical activities through the rubrics. The final marks of the practical part were 8.00 and 8.50 from the courses 2021–2022 and 2022–2023, respectively, according to the procedure established in the methodology section (Table S5, Supporting Information). The marks were slightly higher than the marks obtained in the first part of the course. Grades of 7.30 ±0.5 and 7.80±0.6 were obtained at the end of the introduction part in 2021–2022 and 2022–2023 courses, respectively. These results may indicate the potential of the LbD experience to consolidate LCA concepts acquired during the introduction. Fig. 3 shows the evolution of the overall grades obtained in the Life Cycle Assessment course during the last five years. Note that the number of students in each course is 10, given the limitations of the EPS program. The grades obtained in the last six years remained similar, however, a slight improvement can be observed in the latest years (Fig. 3a). It is remarkable that an improvement of 1.1 points was obtained in the average grades comparing the 2022–2023 year with the first three courses. Note that before 2019–2020 the course was given in a traditional way. Because the sample of students is small, it is necessary to contemplate the overall average of these groups of students. Fig. 3b displays the grades normalised by dividing the average grade obtained in this course by the overall average grade of the EPS module each year. After the normalisation, the improvement of the last two years is clear, which indicates that the practical experience can enhance the learning outcomes of students compared with their average performance in other EPS subjects. Moreover, deviations were reduced from the beginning of the activity, which we relate to a better understanding of concepts and/or that students are more engaged in the activity. A T-student value of 0.08 comparing 2021–2022 and 2022–2023 could suggest that the difference between the groups was not significant. Note that a limitation of the score assessment conducted in this study is the limited sample of students.

3.2. Analysis of acquired competencies

It is well-known that the very nature of open-ended problems demands a distinct and specialised competency set, including problem-solving, creativity, decision-making, and collaboration, among others (Douglas et al., 2012). Because our LbD activity involved problems that were characterised by their multiple potential solutions, inherent data collection, and the requirement for critical thinking and problem-solving skills were asked to students before and after the activity. Fig. 4 displays the results of the competencies acquisition score before the course on a five-point scale (Fig. 4(a)), and the selection of those competencies that were improved after the course (Fig. 4(b)). Note that the results are based on the student's perception, as we consider that self-assessment can be helpful for this purpose. Because the surveys were anonymous and done at different periods of time, the surveys' results are limited and it is not possible to analyse each student's response separately. Future applications of this activity could consider a more detailed evaluation of competencies at the beginning of the course to obtain deeper conclusions.

Before the course, some of the weakest competencies (score below 3/5) were "knowledge of software in the area (*#5*)", "problem resolution (*#7*)", "ability to apply knowledge in practice (*#15*)", "decision-making (*#8*)", "knowledge of a foreign language (*#4*)", "design and project management (*#25*)", "information management capacity (*#6*)", and

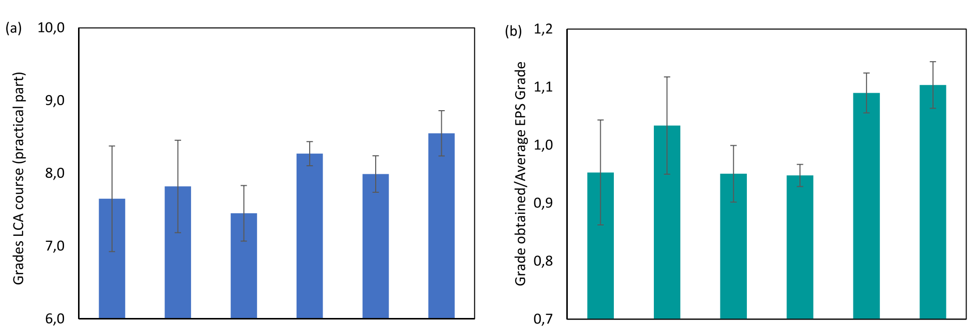
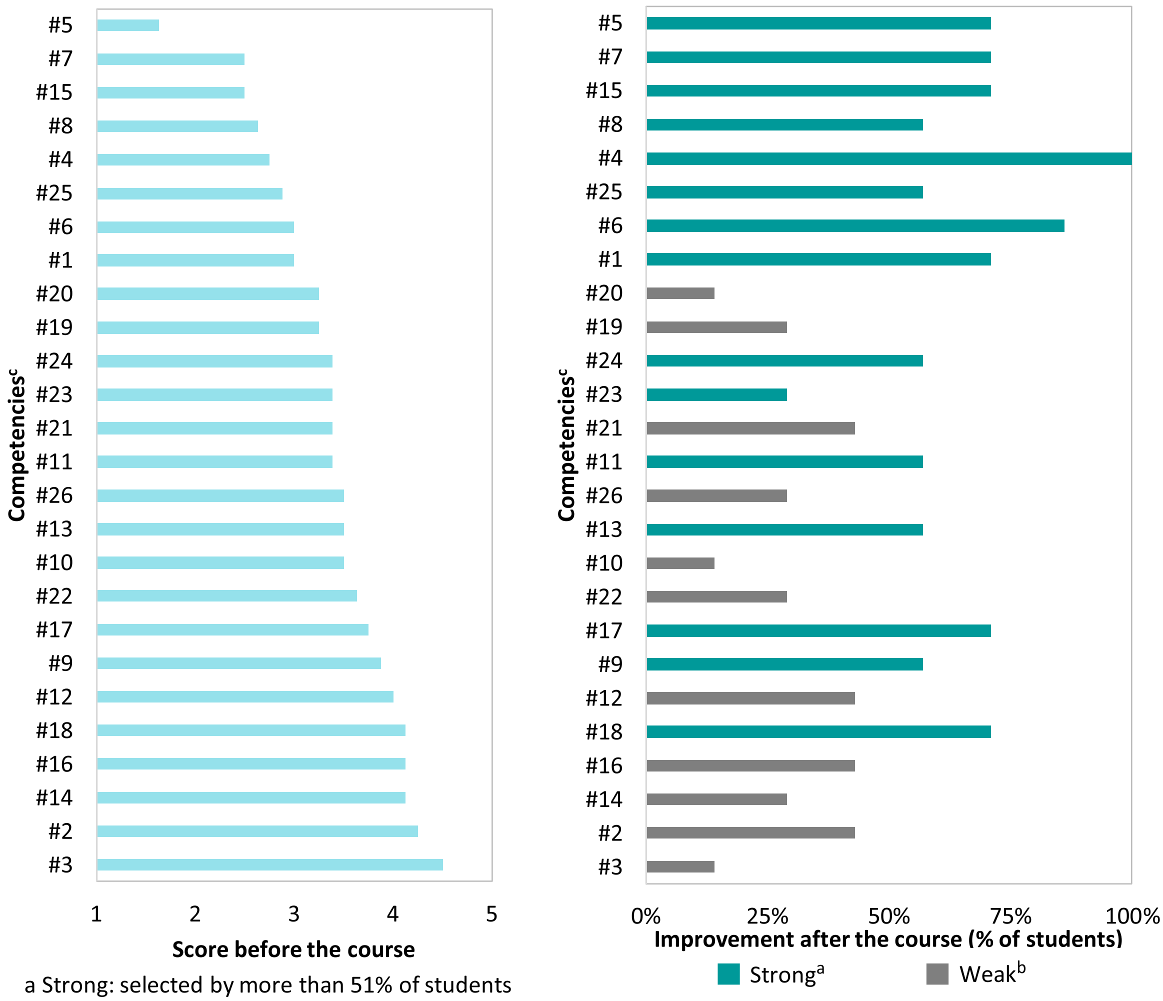


Fig. 3. Evolution of grades during the last five years. * The number of students per course is 10.



a Strong: selected by more than 51% of students
b Weak: selected by less than 50% of students
c Competencies (from #1 to #26) are listed in Table A1 (Supporting information)

Fig. 4. Results of key competencies perceived by students before and after the course.

"capacity for analysis and synthesis (*#1*)". According to the selection of competencies improved after this experience, most of the weakest competencies were improved. More than 75 % of the students selected the improvement of all these competencies, except numbers *#8* and *#25* that were considered to be improved by 57 % of the students. The competencies "oral and written communication (*#3*)", "ability to organise and plan (*#2*)", "recognition of diversity and multiculturalism (*#14*)", "ability to learn autonomously (*#16*)", "ability to work autonomously (*#18*)", and "interpersonal relationships (*#12*)" had a score close to 4 before this course. However, the results from the final survey showed that *#18* was improved by 71 % of the students after this course. Therefore, this activity changed their perception of their ability to work autonomously initially. Because this activity belongs to the international EPS program, it was expected that 100 % of students would answer to improve their knowledge of a foreign language (*#4*). Top interpersonal skills improved after the activity were the "ability to manage the information (*#6*)" (86 %), "capacity for analysis and synthesis (*#1*)" (71 %), "better knowledge of the software in the area (*#5*)", among others (e.g. "adaptation to new situations (*#17*)", "ability to work autonomously (*#18*)", etc.). In fact, we can consider these as key competencies for future LCA practitioners. The interpersonal capacities with the lowest input included the "ability to work in an interdisciplinary team (*#10*)" (14 %), "oral and written communication (*#3*)" and "leadership (*#20*)" (14 %). Capacity (*#3*) was one with the highest initial ranking, so the range of improvement is low. Oral and written communication are promoted in all the subjects by means of oral presentation and reports. Capacities (*#10*) and (*#20*) had before the course a lower ranking (3.5 and 3.25), but these skills are those more complex to acquire by students.

In fact, leadership is a challenge for engineering students and lecturers. According to Thomas (2010), "the rigor, demands on time, expectations of detached professionalism, and technical competence make graduates socially inept". That is the reason of the development of leadership programs and courses, such as Engineering Leaders of Tomorrow Program (LOT) of the University of Toronto. The creators of LOT highlighted that engineers with leadership skills contribute more societal value than those without (Simpson et al., 2012). So, students should strengthen emotional intelligence and self-awareness guided by lectures to improve their leadership competencies.

Because the time-effort they have made was also a critical issue, we analysed their opinion through the final survey. It must be taken into account that the traditional approach of LCA learning involves practical examples focused just on the LCA application instead of dealing with the full reality of LCA practitioners (e.g. lack of data, different estimation approaches, etc.). Therefore, the time-effort, as well as inequalities among groups, were our major concerns. Students worked with different companies and therefore, the availability of real data provided by companies was not equal.

A percentage of 72 % of students considered that the workload was adjusted to their expectations. Analysing the overall results of the survey, the general perception of the students determined that this LbD experience was gratifying and helped them to develop key competencies for chemical engineers as well as for future LCA practitioners (Figure S1, Supporting Information). According to our evaluation, no biases were induced by the case studies developed. In fact, the grades were distributed across the cases-studies. Therefore, the project was balanced in terms of the cost-benefit analysis from the student's perspective and confirmed by the evaluation. To sum up, we can appoint that despite the cost of LbD activities in terms of effort, the outcome was so relevant, and it will be applied in the following courses considering the significant benefits for students, companies and lecturers. The promotion of the benefits of this activity through the companies of the region can increase the interest of companies and their involvement in the following courses. Furthermore, promoting this initiative among Chemical Engineering students could raise awareness about professional competencies that could be acquired by this course as well as the relevance of LCA in their future careers.

From the teachers' point of view, it is vital to analyze the academic evolution of the students but also to consider the importance of sustainability in the chemical engineering curricula. Lecturers have observed how the vision of chemical engineering students in relation to sustainability has been changing significantly over the last decades. Whereas sustainability was in many cases perceived as a passing trend, it is now seen as a necessity in most industrial activities. In fact, these aspects help companies to differentiate their products and introduce them in more competitive markets, highlighting the need for professionals trained in this area.

This change in the sector has led to a greater concern and awareness among students who demand more training in sustainability. This has made students more interested and effective in acquiring competencies in this LCA course. Thus, some of the basic, specific, and transversalcompetencies had already been worked on or even acquired in previous courses.

Students highlighted the improvement of several key competencies and skills for LCA practitioners, such as the "ability to manage the information", "capacity for analysis and synthesis", "better knowledge of an LCA software". Of course, this knowledge is essential within the course, and will help them to develop environmental analysis in their professional life. But one important thing in opinion of the professors, is the great passion perceived on the part of the students, that are motivated to apply concepts learned in class to real cases. We believe that everything that is taught and studied with pleasure is learned and acquired more easily. In addition, some of the social skills acquired by the students seem very positive to us given the current tendency to disconnect from the real world around us or from our own class/workmates through technology. This course has reached an important milestone, to improve the ability to interact and work in teams, essential aspects for future engineers.

This study has provided valuable insights into a practical experience in an LCA course. The student's perception of acquiring general competencies related to LCA practice, such as data management, interpretation, critical thinking, decision-making, and working autonomously, among others, have been analysed. In addition, this is an international course, so we considered other related competencies to multiculturalism. In this sense, it is well-known that LCA professionals often collaborate with practitioners from diverse backgrounds, reflecting the interdisciplinary nature of sustainability and environmental studies. Despite evaluating general competencies supports our main findings, specific competencies related to LCA outcomes may be included in future applications. Future research could benefit from exploring technical competencies in detail, thereby enhancing the integration of LCA into broader sustainability strategies and practices. These competencies, encompassing foundational knowledge, strategy definition skills, analytical capabilities, and sustainable decision-making, are crucial for a comprehensive understanding of implementing LCA practices. In addition, more data will be collected during the following courses to gain more profound knowledge about the benefits of this practical experience, including better statistical analyses. In this sense, we will consider including evaluations from the industries as they can enrich the activity. Future experiences could consider the implication of actively evaluating from the industrial perspective within a collaborative approach. This direction promises to deepen our understanding of outcomes while equipping future practitioners with the necessary skills to apply LCA principles effectively and the professional competencies required for chemical engineers.

4. Conclusions

The LbD methodology has been appointed as a potential strategy to develop key competencies of future engineers. However, application experiences of this pedagogical tool are not commonly found in the area of Life Cycle Assessment. We have introduced satisfactorily a LbD activity in the Life Cycle Assessment course of the Chemical Engineering Degree at UC, which has allowed us to evaluate the promotion of student engagement in the practical part of the course and, specifically, the professional competencies acquired. Students have worked as LCA practitioners analysing the environmental performance of real case studies in collaboration with industries of the region of Cantabria (Northern Spain). Weekly sessions have been used to assist students by the lecturer team. They have followed up on the student's engagement, initiative and achievement of the tasks proposed at the beginning of this activity. Students have had to overcome some difficulties in finding data to build up life cycle inventories. This has pushed them to manage several kinds of challenges that are commonly found in real LCA practice.

The main hotspots identified when working with real companies include to maintain a regular and consistent communication and ensuring that the data collection is done under an ethical conduct. Because confidentiality agreements could be an obstacle to use real data students overcame the gap of lack of data by consulting the public Spanish Integrated Environmental Licence of the companies, the Spanish Pollutant Release and Transfer Register (PRTR) and, when needed, they carried out estimations and approximations when needed under the supervision of the lecturer team. The defence was done in a public session along with the company contacts involved. Representatives gave feedback to make the adjustments and corrections needed while valuable information about sustainability was received by them. This experience enriched this course as it not only provided an opportunity to reinforce LCA fundamentals but also offered a tool to enhance many professional skills of Chemical Engineers. An improvement up to 1.1 points was reached through this experience in comparison with the previous courses. The results of the survey conducted at the end of the activity demonstrate that students considered that this activity helped them to improve several key competencies, which are essential for LCA practitioners highlighting the "ability to manage the information", "capacity for analysis and synthesis", "better knowledge of the software in the area", among others. Furthermore, 71 % of students answered that they put into practice their chemical engineering knowledge. According to the lecturers, the competencies acquired by students through this LbD experience in life cycle assessment have notably evolved, demonstrating not only an enhanced understanding of environmental impacts across a product life cycle, but also a significant improvement in critical thinking, team collaboration, and practical problem-solving skills, thereby bridging the gap between theoretical knowledge and its application in real-world scenarios. In addition, through this experience, both lecturers and industry have benefited, as the course has had industrial relevance, demonstrating how the LCA tool can satisfy the requirements of industrial partners. A win-win-win situation has been created, in which the students have been actively engaged working as LCA practitioners, while the collaborating companies have got useful insights to improve their environmental performance.

CRediT authorship contribution statement

Jonathan Albo: Conceptualization, Funding acquisition, Investigation, Methodology, Validation, Writing – review & editing. **María Margallo:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Writing – review & editing. **Javier Pinedo:** Conceptualization, Investigation, Writing – review & editing. **Marta Rumayor:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ece.2024.05.002.

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