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Learning-by-doing: Experience from 20 years of teaching LCA to future engineers

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Abstract

Purpose

In support of the sustainable development of our societies, future engineers should have elementary knowledge in sustainability assessment and use of life cycle assessment. Publications on pedagogical experience with teaching LCA in high level education are however scarce. Here, we describe and discuss 20 years of experience in teaching LCA at MSc level in an engineering university with the ambition to share our insights and inspire teaching of LCA as part of a university curriculum.

Methods

We detail the design of an LCA course taught at the Technical University of Denmark since 1997. The course structure relies on (i) a structured combination of theoretical teaching, practical assignments and hands-on practice on LCA case studies, (ii) the conduct of real-life LCA case studies in collaboration with companies or other institutions. Through the semester-long duration of the course, students from different engineering backgrounds perform full-fledged LCA studies in groups, passing through two iterations – a screening LCA supporting a more targeted LCA.

Results and discussion

The course design, which relies on a learning-by-doing principle, is transparently described to inspire LCA teachers among the readers. Historical evolution and statistics about the course, including its 192 case studies run in collaboration with 105 companies and institutions, are analysed and serve as basis to discuss the benefits and challenges of its different components, such as the theory acquisition, the assignment work, the LCA software learning, the conduct of case studies, the merits of industrial collaborations, grading approaches, etc.

Conclusions and recommendations

We demonstrate the win-win situation created by the setting of the course, in which the students are actively engaged and learn efficiently how to perform an LCA while the collaborating companies often get useful insights into their analysed case studies. The course can also be an eye opener for companies unfamiliar with LCA, who get introduced to life cycle thinking and the potential benefits of LCA. We have no hesitation in recommending industries and LCA teachers to engage into such collaborations even in the fundamental teaching of LCA techniques.

Keywords

LCA teaching, life cycle assessment, education, engineering students, university teaching, course, case study, active learning, industrial collaboration

1 Introduction

Education of future engineers, managers and other decision-makers is key to enabling our society to tackle sustainability challenges (Boyle 2004; Olsen 2010). Professionals entering the labour market help raising awareness about sustainability in our society, industry and institutions if they (i) know what sustainability is and how to incorporate it into their decisions, (ii) are knowledgeable of the necessary methods and tools, and (iii) are able to apply these in the assessment of sustainability (Laurent et al. 2015).

Life cycle assessment (LCA) is used as a decision support tool in various technological domains and disciplines (Curran, 2012; Hauschild et al. 2017), but literature on pedagogical experiences and applications is scarce (e.g., Cooper and Fava 2000a, b; Evans et al. 2008; Lin et al. 2012; Masanet et al. 2014; Mälkki and Alanne 2017), despite a sizeable number of dedicated LCA guidance and teaching books (Baumann and Tillman 2004; Consoli et al. 1993; Curran 2012, 2015; Guinée et al. 2002; Hauschild and Wenzel 1998; Hauschild et al. 2017; Heijungs and Suh 2002; Jolliet et al. 2016; Klöpffer and Grahl 2014; Lindfors et al. 1995; Matthews et al. 2015; NCM 1992; Wenzel et al. 1997; White and Schenck, 2014; UNEP 1996).

A variety of quantitative sustainability assessment tools, teaching methods and technological domains covered in LCA case studies (see examples compiled by Mälkki and Alanne (2017)) have been used to teach sustainability assessment and management to students. Regardless the range of complexity and scope of these courses, the objective of educating future managers, decision-makers, and researchers is recurrent. In this effort, structured case studies are, above all, considered important to develop the required life cycle thinking and systems literacy (see e.g. Gilmore 2016).

This paper describes and discusses the content and structure of a course introducing LCA as a tool for sustainability assessment that has been running and continuously developed for two decades at the Technical University of Denmark (DTU), directed to students at Master of Science (MSc) level. To increase the acquisition and application of sustainability knowledge and the command of its available tools, we believe that the technical qualification of the students and the continuous and effective LCA education are essential. The teaching strategy is to meet this objective through an active learning-by-doing experience, where we have experimented with different course settings over the past two decades to continuously improve and strengthen the education of future engineers. The ‘success stories’ of trained LCA practitioners, researchers and other professionals, and the involved industrial collaborations and partnerships, as reported in this paper, are intended to (i) impart inspiration for other LCA course providers who seek to improve or revamp their teaching methods, and (ii) make industrial stakeholders aware of opportunities and benefits offered by engaging in direct collaboration with university courses in the form of real-life industrial cases (Hauschild et al. 2012). The various resources provided as supporting information will be useful in the implementation of some of the elements in the teaching.

The course is named "Life Cycle Assessment of Products and Systems" and is currently part of the technological specialization curricula in several MSc programmes at DTU. To serve as inspiration for LCA teachers at university level, we showcase our course design (Section 2) that enables students to become proficient, generic LCA practitioners. After illustrating the performance over the past 20 years (Section 3), we discuss challenges in consideration of future teaching/learning trends and transferability of the course design to other settings (Section 4).

2 Course design

The consistent application of the pedagogical principle of 'learning-by-doing' lends a particular effectiveness to the course, in the form of individual assignments as well as iterative LCA application to industrial case studies performed in groups. The main strength of the course thus resides in the alignment between the learning objectives (Section 2.1), the teaching activities (Sections 2.2 and 2.3), the assessments (Section 2.4) and the practical work (Section 2.5), all consistently based on this principle.

2.1 Overall course composition and learning objectives

The course is currently structured into two weekly sessions over a 13-week semester, usually divided into a 4-hour lecture-based session and a 4-hour hands-on session with tutors. Throughout the semester, the workload typically shifts from acquisition of new knowledge to its application in practice (Fig 1A). The last three weeks of the semester are usually taken in full for tutored group work on the case studies. Generally, the students are expected to use about the same amount of time for individual learning and homework, so that the total learning time per student is approximately 280 hours during the whole semester, equivalent to 10 ECTS (European Credit Transfer System) points (see distribution of this workload in Fig. 1B). A total of 35 hours are allocated for lecturing on concepts and methodology, which amounts to ca. 13% of the course workload (Fig. 1B). About 50% of the course time is assigned to group work on the case studies (including tutored and unsupervised sessions), while the remaining time is dedicated to the completion of the individual assignments and the reading of the supporting material (Fig 1B).

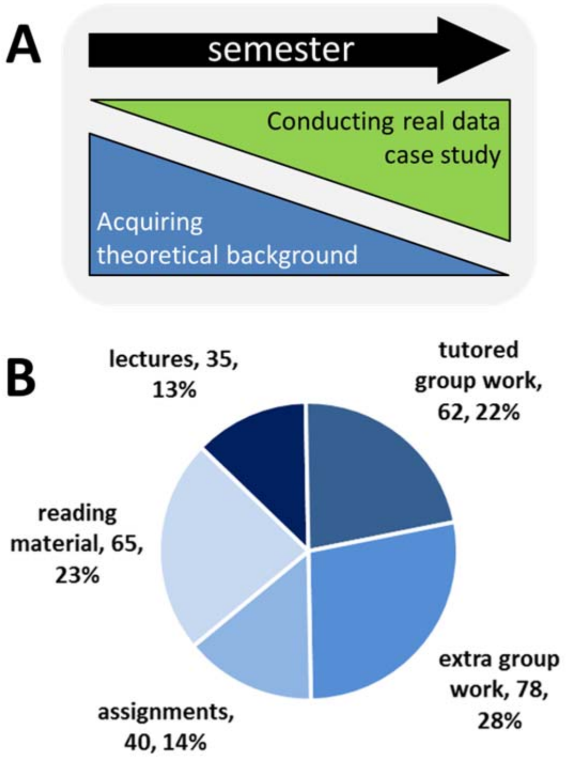

Fig 1 (A) Schematic workload allocation shift throughout the semester; (**B)** Distribution per task in a 13-week semester (given in hours and %) and amounting to 280 hrs (10 ECTS).

The learning objectives (LO) of the course are listed in Table 1. They cover the entire range of complexity levels according to the Bloom's taxonomy (Bloom et al. 1956), from basic level I 'remembering' and 'understanding' that require the retrieval of previous knowledge on e.g. environmental issues, engineering concepts related to environmental management, life cycle of production systems, environmental chemistry or physics, to higher levels that involve deeper cognitive processes to apply new concepts and 'analyse', 'synthesize' or 'create'. While the lower levels are typically useful when introducing new concepts, the emphasis of the course is mainly set on the higher level LOs – students are required to critically apply their knowledge in the assignment and group report.

Table 1. Learning objectives of the course 'Life Cycle Assessment of Products and Systems'

1. **Demonstrate** a fundamental understanding of life cycle thinking in the analysis and management of technological systems (lower levels of Bloom's taxonomy – remembering, understanding; Bloom et al. 1956)
2. **Explain** the most important industrial and regulatory applications of LCA and **describe** the tools of Integrated Product Policy, IPP (lower levels of Bloom's taxonomy – remembering, understanding; Bloom et al. 1956)
3. **Plan** and **execute** a life cycle assessment of a product or a technological system in co-operation with a company or other type of organisation (all six levels of Bloom's taxonomy – remembering, understanding, applying, analysing, synthesising, evaluating; Bloom et al. 1956), including:
    4. **Define** a relevant functional unit for a product or a system;
    5. **Ensure** equivalency of products or systems through system expansion or allocation;
    6. **Model** an inventory using a dedicated LCA tool;
    7. **Perform** characterisation, normalisation, and weighting;
    8. **Perform** sensitivity analysis and interpret the results of the LCA in accordance with the outcome;
    9. **Report** in accordance with the capabilities of the company partner;
    10. **Develop** proposals for the application of the results and for further analyses based on the LCA;
    11. **Explain** the assessment parameters which describe the impacts on environment, work environment, and resources.
12. **Interpret** and **use** life cycle assessments performed by others and perform a critical review of an LCA study (higher levels in Bloom's taxonomy – evaluating; Bloom et al. 1956)

2.2 Constructive alignment

Students experience a combination of (i) lectures focused on LCA theory and methodology along with exercises that require active participation in discussions, (ii) individual assignments, where their knowledge acquisition is evaluated throughout the course, and (iii) group work in performing an LCA on a real-life case study (illustrated in the vertical axis in Fig 2). During the semester, students progressively acquire knowledge on the various LCA phases and apply it to their industrial case study (illustrated in the horizontal axis in Fig 2).

During the knowledge acquisition, the planned activities within each week are internally aligned. Lectures introduce specific points of the LCA methodology, which are then checked via individual assignments and further applied to the case study in the group work session in the same or the ensuing week. This constructive alignment is ultimately verified by the application of the theoretical and practical knowledge (gained from the lectures, reading materials, and assignments) into the LCA report delivered at the end of the semester as a result of the group work on an industrial case study.

The teaching activities and students' participation are designed with a two-fold purpose: activate the students during classes and promote active learning by means of short problem-solving activities to apply and consolidate the knowledge acquired. Continuous feedback during the lectures (by the teacher), assignments (by peer students), and throughout the group work (by the tutors), help at (self)-evaluating progress.

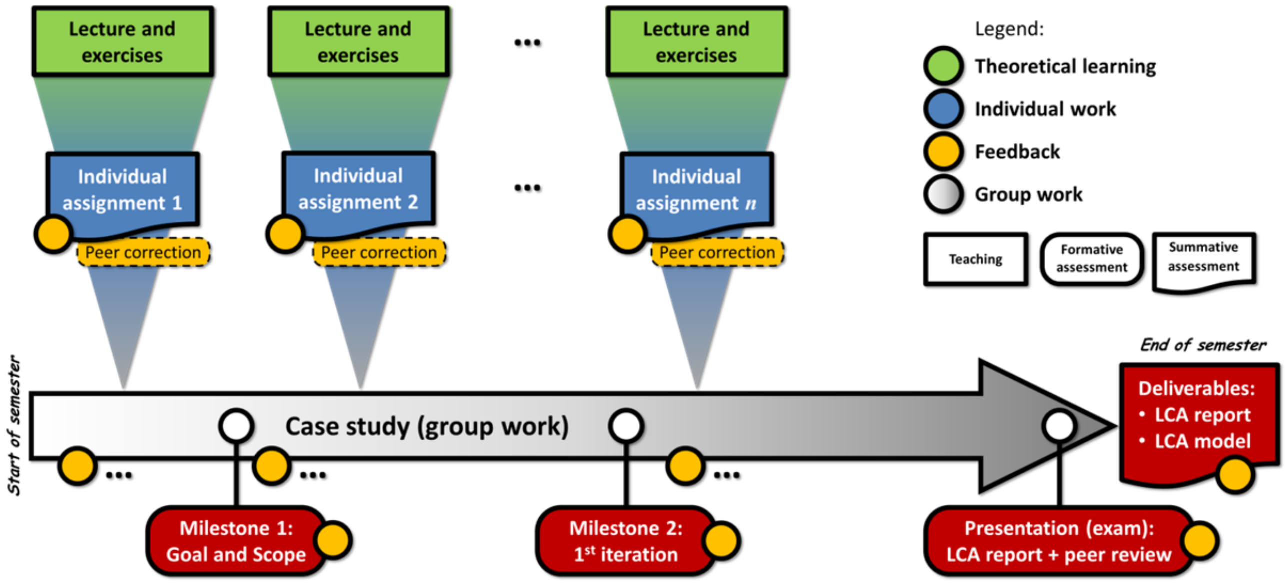

Fig 2 Course design with the identification of teaching activities (green square boxes) and assessment moments as progress milestones (red rounded boxes), and course deliverables (waved red box). Feedback is given on students' learning progress in the individual assignments, peer corrections, case study applications, milestone deliverables and final reports. The vertical axis illustrates knowledge acquisition and the horizontal axis illustrates semester progress and knowledge application with major milestones.

2.3 Theoretical background and reading material

The lectures, complemented by the reading material (with prior or subsequent consultation, depending on the student's habits and preferences), introduce in detail each phase of the LCA methodology, i.e. goal and scope definition, inventory analysis, impact assessment and interpretation (ISO 2006). Dedicated lectures are assigned to particularly challenging aspects in the conduct of LCA to ensure true assimilation by the students, e.g. via plenum discussion and in-class exercises. An example is the handling of multifunctional processes in the scope definition and product system modelling, including the application of subdivision, system expansion, and allocation. The detailed planning and distribution of the lecture topics is provided in Table S1.

The reading material has evolved through the years (see Section 3.1.3 for detailed description). However, the background information for the LCA methodology has always been in line with the ISO 14040-44 standards (ISO 2006) or their predecessors in the first decade of the course, thus following all four major phases of the LCA methodology and their associated requirements.

2.4 Individual assignments

The assimilation of the concepts and methodological principles is checked by means of weekly or fortnightly graded assignments in phase with the lectured topics, thus covering all four phases of the LCA methodology. The contents and learning objectives of each assignment are aligned with the theoretical background given in the lectures and covered by the allocated reading material. This ensures alignment and continuity of the course contents, and allows the students to be exposed to the same information in three distinct learning moments (lectures, reading, and examination) – these correspond to passive and active knowledge acquisition and checking of the acquired knowledge. An overview of the themes and learning objectives of each individual assignment (from the current version of the course) is documented in Table S2. Assignment texts for all assignments are available in Supplementary Material (as part of Supplementary Methods); model solutions can be obtained upon request made to the authors.

Peer correction and peer grading were introduced in recent years (since 2014; see Section 3.1.4) with additional learning objectives within the assignments tasks. Peer correction (with or without grading) exercises the students' analytical skills, as they have to critically (and anonymously) judge the quality and completeness of the answers in a colleague's assignment. Beyond ensuring that the students get a thorough reading of the exercise solution, the peer correction finds similarities with the peer review process of journal manuscripts, in which reviewers may learn about the strengths and weaknesses of their own writing, effective writing techniques, feedback-giving skills, and typical pitfalls. Students may use the peer-review as an opportunity to understand the correct answer (solutions are given prior to peer correction) and/or, if needed, to seek explanations in the lectures and reading material.

2.5 Industrial case studies

In parallel to the lectures and individual assignments, the students are introduced to actual LCA practice by conducting a group project on a real-life and real-data case study in which they apply the LCA methodology shortly after being introduced to it. The specificity of these case studies, and the reason why we classify them as "real-life", is that they are coming directly from an industrial partner (typically representing a real question the partners seek an answer for) and are executed in direct contact between the students and the industrial partner, like in a real-life situation of an LCA consultant. The groups are formed by the teaching staff and typically have 4-6 members selected to ensure a good match between the combination of backgrounds and competences in the group and the type of case study (e.g. assessment of a soil remediation system may fit better environmental engineering students than architectural engineering students). Given the relatively important workload, a group size of 4 or 5 students has been found optimal to make the group function efficiently and enable "visibility of all students and accountability in their contributions", as formulated by the University of Sydney (2018). Groups of 6 students, which cannot always be avoided (e.g. due to a limited number of retrieved case studies) increase the risk of "inactive" students, who contribute little to the group effort and compromise the team spirit. Such situations are prevented as much as possible through the frequent supervision and monitoring of the group by the teaching assistants (see Section 2.5.3).

2.5.1 Rationale for having real-life case studies

Through the industrial case studies, the students, who interact directly with the case companies in the role of student "consultants", are confronted with each of the actual steps of performing LCA, including the inherent challenges, notably data collection. They learn how to plan, scope and run a LCA case study, they discover what is effectively required behind each methodological step, in terms of transforming an industrial problem/question into an LCA (scoping), data collection, assumptions, calculation, and reporting, they recognise where the pitfalls and main uncertainties lie and they learn how to overcome methodological difficulties (e.g. data collection and treatment, result analysis and communication, etc.) as well as organisational challenges (e.g. team work, communication with companies, meeting deadlines, etc.).

Furthermore, the students acquire an understanding of the iterative nature of LCA and of its importance in the refinement of the LCA case studies to better answer the question posed in the goal definition and to provide reliable support to decision-makers. Through imposed deadlines in the course syllabus, the students are led through two complete iterations, the second one leading to the final deliverable from the case study (see Section 2.5.3).

An important advantage of having real-life case studies is that it actively engages the students. Because the case studies are industry-driven, there is a real interest and/or curiosity from the companies providing the case studies. This often feeds into an interactive and synergetic collaboration between the students and the companies, where both parties actively work to make the case study a success –far beyond the mere realisation of a course project. This interaction has a very tangible, positive effect on the students' motivation and activation and there have been several cases where students were employed by the industrial partner after their graduation as a direct consequence of this interaction.

2.5.2 Finding and selecting case studies

The case studies are sought and prepared by the teaching staff, typically over the three months prior to the start of the course. Industries and organisations of all sizes, from small locals to multinational, which are part of the teaching staff's network, are contacted, introduced to the course purpose and content, and asked whether they are interested in providing one or several case studies for a LCA. Companies are informed that, although a full LCA is performed, the LCA report delivered to them still remains student work and cannot be regarded as a consultancy-level work. Despite this, the case studies often bring useful insights to the company, thus turning the collaboration into a win-win situation for both students/teaching staff and case providers.

Typical case studies are either (i) comparative, involving assessments of several alternatives for supporting product/system development (e.g. facilitate choice between different solutions) or for benchmarking against existing products/technologies, or (ii) individual product-/technology-focused analyses, where the largest impacts are identified in the life cycle of the systems under study to feed into recommendations to stakeholders (e.g. weak-spot analyses).

Two major requirements frame the acceptance of the case studies in the course: (i) the company must have sufficient case-specific or site-specific data available to perform the LCA (e.g. bill of materials, energy requirements, supplier locations, etc.), and (ii) the company must engage itself to have a contact person available to the students, particularly for answering the questions pertaining to the goal and scope definition and for supplying the data in the life cycle inventory (LCI) phase. These aspects are discussed between the companies and the teaching staff during the case elaboration prior to the course start (see Supplementary Methods documenting the used support template). Although some mishaps may happen during the semester (e.g. unresponsive contact person, companies not delivering the data), these proactive steps very often ensure a smooth and effective collaboration between the companies and the students during the course semester, and many companies have provided case studies repeatedly over the two decades. To make the case as representative as possible, companies are also informed of the possibility to have the students sign non-disclosure agreements to elude any confidentiality-related hurdles in the collection of site- or product-specific data (LCI phase).

2.5.3 Milestones and feedback

As illustrated in Figure 2, the students are introduced to the iterative nature of LCA, i.e. going through all LCA phases and back again to refine the assessment, through two major milestones: (i) the delivery of an interim LCA report containing a first iteration of the case, complemented by a plenum presentation in front of peers and the teaching staff (about two thirds into the course semester); and (ii) the delivery of a final LCA report, containing the second iteration of the case and also complemented by a plenum presentation (at the end of the course). The interpretation of the work after the first iteration is directed towards identifying focus points for the work in the second iteration through identification of key data and assumptions with high uncertainty. An additional milestone is also set ca. three weeks after the start of the project work, where the students hand in an interim report on their goal and scope definition and present it in plenum. In addition to the course material, specific textbook chapters help the students meet these milestones, including a "cookbook" providing detailed guidance for applying each LCA step (Hauschild and Bjørn, 2018), a "reporting template" (Bjørn et al., 2018) and an example report (Owsianiak et al., 2018). For interested readers/lecturers, example reports made by students in the course can also be obtained upon request to the authors.

Each group is supervised by a teaching assistant (TA), who follows the students' progress through the entire semester. Teaching assistants, who are either PhD students or MSc students having previously followed the course successfully, are typically responsible for 3-5 groups each. They are available to their groups at the 4-hr supervised group work sessions every week of the semester (see Figure 2) and upon appointment. The TAs also check and comment on each of the three reports delivered by the groups at each of the milestones, and both written and oral detailed feedback is provided to each group. For the final report, the senior teaching staff also assesses the reports, and a grading session is organised with all TAs and teaching staff (see Section 2.6) in order to establish a consensus-based grading.

The final presentation of the case studies is organised as a mini-seminar, where company case providers are invited to participate. The format of each case presentation is divided between a 10-minute presentation of the case results by the student group, followed by a peer-review of the associated report prepared beforehand and presented by another student group (10 minutes), and finally recapped by a question/answer session of 5-10 minutes open to the audience. Each student group is thus assigned another case report to critically review according to the guidelines defined by Weidema (1997) and the LCA methodological guidance introduced throughout the course. This last step in the course aims to make the student become proficient readers of LCA studies, i.e. being able to critically assess the quality and reliability of LCA studies (cf. learning objective 11 in Table 1).

2.6 Assessment of student deliverables

The individual course grade is based on an equal weight ratio (50:50 %) between the grade conferred to the group report (on the case study) and the (simple or weighted) average grade awarded to the individual assignments.

Assignments are assessed against a solution model prepared by the teaching staff. The grades are awarded as a function of completeness and correctness of the answers provided (linked to the learning objectives of the assignment; see Section 2.4). Feedback is always provided promptly to the students on their performance in each assignment. The format of this feedback has evolved over the years, from collective feedback on most problematic aspects to individual and detailed feedback (see Section 3.1.4).

Group reports are assessed based on (i) overall compliance with the LCA methodological requirements and guidelines, (ii) completeness and suitability of the LCA model and interpretation of the results with respect to the goal and scope of the study, and (iii) overall success in consistently reporting and communicating the LCA study in a structured and adapted format to the target audience (i.e. company stakeholders). The assessment should reflect the fulfilment of those learning objectives that are relevant to the planning and execution of the LCA case study (see LO 3-11 in Table 1). These criteria ensure that the group work grade is not dependent on the extent and quality of the LCI information received from the company and the LCIA results as such (although consistency, completeness and sensitivity of the LCIA results are required to be checked). Instead, the grading is focused on the students' proficiency to apply the acquired LCA knowledge, hence assessing (a) their ability in coping with the definition and scoping the system under focus; (b) the data handling (source identification, collection, evaluation of quality, assumptions requirements); (c) the modelling of the system (software use); (d) the obtaining of results; and (e) the analysis and discussion (quantitatively and qualitatively) of the findings in light of the defined goal of the study (is the question answered?) and the different assumptions and uncertainties underlying in the scope definition, LCI and LCIA phases. An evaluation scheme, detailing criteria for these aspects and helping harmonise the grading of the LCA reports, is used by the TAs and teaching staff –see Table S3.

At the end of the semester, collaborating companies are invited to attend the final presentations made by the students (about the company case itself as well as other groups' presentations; see

Section 2.5). Here, they can participate by directly questioning the presenting groups and commenting on the work performed. Case study companies also receive copies of the final reports and all material produced for their cases (e.g. LCA model), supplemented with feedback from the teaching staff on the overall quality and reliability of the report and on potential critical aspects in the study.

3 Course performances in practice

3.1 Evolution of course design over the last 20 years

The course has been running since 1997 and experienced a growing interest over the years. A total of 1044 students have enrolled in this course. In 2015-2016 (last years of the current study), it peaked in attracting around 100 students annually (Figure 3).

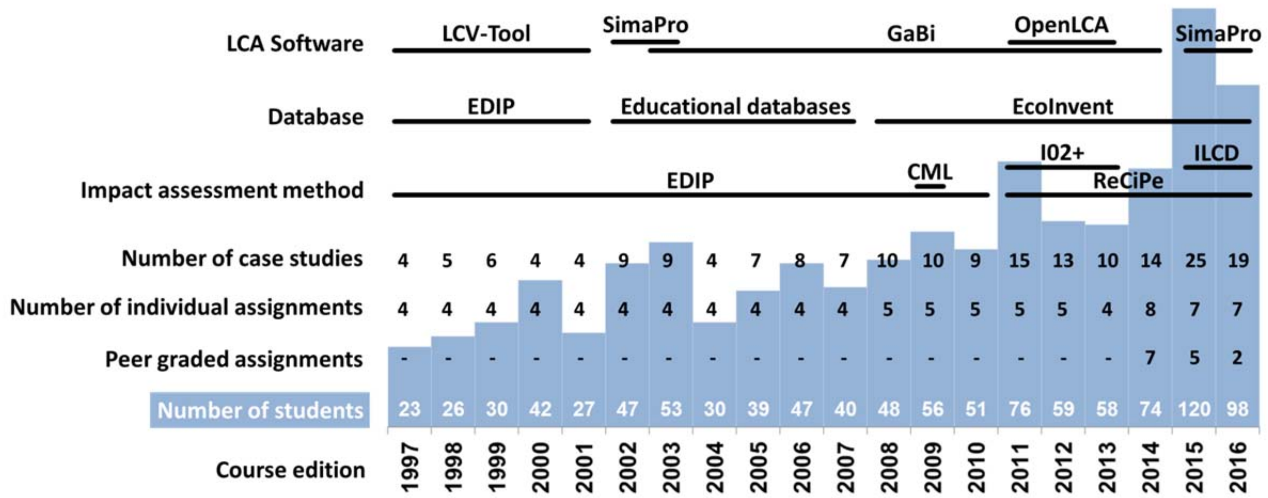

Fig 3 Historical data of LCA course given at the Technical University of Denmark over 1997-2016.

3.1.1 Student backgrounds

The students come from a variety of backgrounds and show different motivations and interests when deciding to enrol in the course. Their study programmes can be grouped into ‘Environmental Engineering’, ‘Design and Innovation’, ‘Building/Materials/Transport’, ‘Energy/Chemistry/ Biological Sciences’, ‘Management Engineering’, and ‘Other study lines’ (Figure 4A). The annual distribution among these study programmes is strongly dependent on which study lines recommend the course to their MSc students. This explains the fluctuations observed in Figure 4, and the gradual diversification of study programmes as more study lines recommended the course over the years. The course has been taught in English during the entire period, which is essential to overcome the language barrier for a significant share (ca. 50%) of foreign students (Figure 4B), who may be enrolled in full MSc or PhD study programmes, temporary exchange students (e.g. under the ERASMUS programme), or guest students from other universities. Danish students represent on average 44% of the population of students in the LCA course over the last two decades, followed by students originating from Southern European countries (e.g. Greece, Italy, Spain, Portugal).

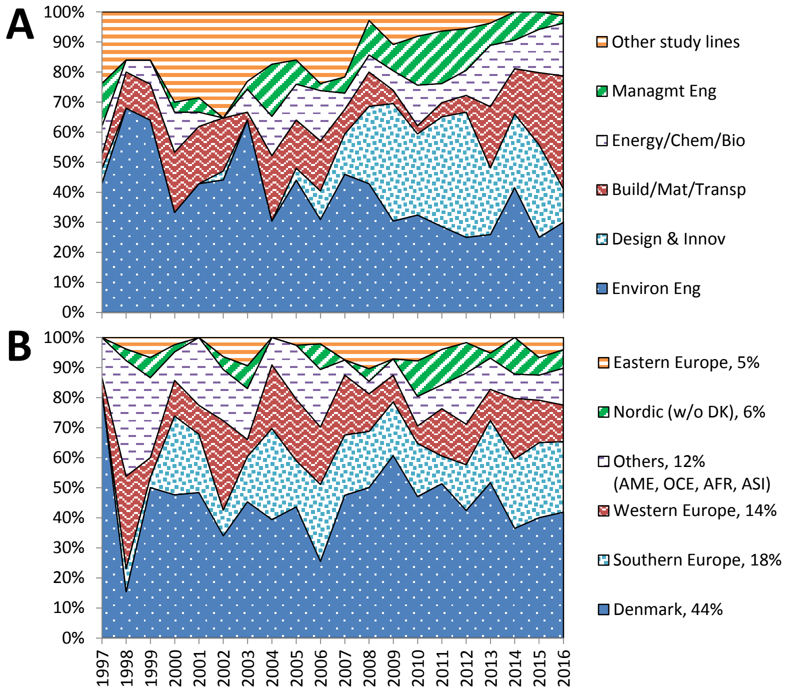

Fig 4 Study lines (**A**) and geographic origin (**B**) of the students enrolled in the LCA course per year. Study lines: '*Environ Eng*': Environmental Engineering; '*Design & Innov*': Design and Innovation; '*Build/Mat/Transp*': includes Civil Engineering, Architectural Engineering, Industrial Design and Engineering, Mechanical Engineering, Transport and Logistics; '*Energy/Chem/Bio*': includes Chemical Engineering, Biochemical Engineering, Systems Biology, Electrical Engineering, Wind Energy, Petroleum Engineering, Food Technology, Sustainable Energy; '*Managmt Eng*': Management Engineering; '*Other study lines*': includes other engineering backgrounds and PhD students, etc.

3.1.2 Modelling software and impact assessment methods

Training with LCA software tools has changed over the last 20 years. Initially (1997-2001), we used the EDIP LCV-Tool (Institute for Product Development, IPU – Lyngby, Denmark) developed under the Environmental Design of Industrial Products (EDIP) project (Wenzel et al., 1997, Hauschild and Wenzel, 1998) under which the course was originally developed. After 2001, and depending on the year, we have used alternatively or conjointly OpenLCA (GreenDelta – Berlin, Germany), GaBi (Thinkstep – Stuttgart, Germany), and SimaPro (Pré Consultants – Amersfoort, Netherlands), running with educational LCI databases in the first years and including the ecoinvent database after 2008 (ecoinvent – Zurich, Switzerland); see history in Figure 3. The selection of LCA software is a function of several considerations, including (i) the practical usability of the software (user-friendly interfaces, stability, update access), (ii) the affordable number of licenses in relation to numbers of students attending the course (see also Section 4.3), and (iii) the professional use of the LCA software by companies (to introduce students to tools most likely to be encountered later in their career).

Likewise, the methodologies used for the LCIA phase have evolved over the years, with the use of EDIP97 (Wenzel et al. 1997; Hauschild and Wenzel 1998), EDIP 2003 (Hauschild and Potting 2005), CML 2002 (Guinée et al. 2002), IMPACT 2002+ (Jolliet et al. 2003), ReCiPe (Goedkoop et al. 2009; Huijbregts et al. 2016, 2017) and ILCD (EC-JRC 2011; Hauschild et al. 2013) LCIA methodologies (see Figure 3). The selection is motivated by the combined consideration of the latest LCIA method developments, the method availability in LCA software and the match with the course material (e.g. EDIP methodology matched with use of EDIP 1997 and EDIP 2003 as LCIA methodologies).

3.1.3 Reading material

From 1997 to 2010, the EDIP textbooks on life cycle assessment were used as primary support for the course (Wenzel et al. 1997; Hauschild and Wenzel 1998). The EDIP methodology was developed in the early 1990s and updated in 2003 as the outcome of a large Danish LCA and eco-design methodology development project Environmental Design of Industrial Products (EDIP) and documented in a two-volume textbook set (Wenzel et al. 1997; Hauschild and Wenzel 1998) targeting university students and industry professionals.

After 2010, the course reading material was revised to integrate latest LCA knowledge and guidance. The provisions and guidance of the detailed guidelines on LCA practice from the ILCD Handbook, published by the EU Commission in 2010, were then used as primary support (EC-JRC 2010). The highly technical presentation of the ILCD Handbook, combined with its writing-style rather addressing LCA experts than newcomers, however, turned out to be challenging for many students, who, despite the lectures, had difficulties to assimilate the guidelines. Draft methodological chapters of the LCA textbook by Hauschild et al. (2017), which provides detailed

LCA guidance in a more pedagogical manner, were thus developed from 2011 onwards and used in 2013-2016, and this textbook (published in 2017) will be used in forthcoming editions of the course.

Scientific articles, method reports, book chapters, and other literature relevant to specific points of the course, focusing on both the LCA methodology (e.g. method development and application in LCI or LCIA) and the implementation within industry (e.g. ecolabelling or EPD process, life cycle management) are also used as teaching materials in the course. Such links to development and application are typically complemented by lectures given by both in-house experts and invited guests from academia, industry and authorities (e.g. invited lecturers from *Ecolabelling Denmark* to introduce the use of LCA in ecolabelling). The new textbook has an extensive coverage of different applications of LCA and its use in many technology domains to support this part of the teaching.

3.1.4 Assignments

As illustrated in Figure 3, the number of assignments has varied from four comprehensive, workload-heavy assignments with 2-3 weeks of preparation time (i.e. one assignment per LCA phase), to eight and lately seven relatively short assignments, typically limited to 1-2 weeks of preparation time (i.e. two assignments per LCA phase). This change has been implemented to distribute the student workload more evenly over the theory acquisition phase of the course, and to better align the assignments with the lecture topics in each week. The questions, exercises and/or data for the calculations typically vary from one course edition to the next to prevent students from cheating and using solutions from previous years.

Although the assignment focus areas, which follow the LCA phases, have largely remained unchanged, two topics have seen evolutions: (i) an assignment on social impact assessment, e.g. work environment, which was run in the period 1997-2010, has been removed from the assessment to prioritise other topics of the course (social LCA is still being introduced in the course); and (ii) an assignment focused on the use of LCA software has been introduced in 2014, which the students perform in groups of two to strengthen individual knowledge of LCA modelling. All assignment texts from the current course edition are available in Supplementary Material (see also Section 2.4); model solutions can be obtained upon request made to the authors.

As described in Section 2.6, major emphasis has been given to provide adequate and timely feedback to the students, progressively moving from a mostly quantitative format (marked per question in percentage of compliance with the solution and by collective feedback on key misunderstandings) to a written qualitative feedback for each answer. This feedback has been reinforced by the implementation of peer grading in 2014-2016 (see Section 2.4), which was teacher-graded in the last two years to ensure seriousness in the student work.

3.2 Case study evolution

Since the course was implemented, 192 case studies have been performed in collaboration with 105 companies. Although strongly dominated by industry, the term 'companies' here also includes organisations counting governmental and non-governmental bodies and agencies, academia and research centres. The collaboration so far counts 44 small- and medium-sized enterprises (SMEs, i.e. under 250 employees) and 61 large companies, hence 42% and 58%, respectively. Interested companies typically renew their collaborations, and some of them have provided case studies for several years; Siemens thus supplied 23 case studies since their first collaboration with the LCA course in 2009. The topics of the case studies vary considerably, with products and services stemming from sectors such as waste management, furniture, packaging solutions, roads and building industry, food industry, electrical equipment, manufacturing industry, and even funerals. Most frequently assessed types of products/services are shown in Table 2, and a complete list of the 192 case studies is documented in Table S4. The numbers of case studies and companies involved per year have grown mainly as a function of the number of students, as each case study group is limited to 4-6 students. We try to limit having multiple groups working on the same case and new cases have been found each year to avoid plagiarism from the students and avoid overload of company contact persons. As illustrated in Figure 3, from an average of five industrial cases and three companies in the first five years of the course, the course has evolved into a massive number of 20-25 cases and around 15 companies in 2015 and 2016, thus also putting increasing pressure on the search for case studies (see Section 4.5).

Thanks to the progressive accessibility to professional LCA software and LCI databases, the quality of the LCA case studies performed in the course has improved in consistency. This has contributed to make the case studies increasingly relevant to companies that could use the delivered LCA report to gain LCA insight, to support EPDs, product development, eco-design decisions, and/or development of an LCA capacity within the company (e.g. development of tools based on assessment of product family in course). For interested readers, example reports made by students in the course can also be obtained upon request to the authors.

Table 2. Top product/service categories in case studies of LCA course over 1997-2016.

Category of products/services	Number of cases
Construction material	31
Technology	27
Electrical equipment	24
Materials	18
Furniture and furnishings	16
Waste management	18
Machinery	14
Food industry	12
Packaging	12
Garment and textile products	9
Hospital products and personal care	6
Service	3
Others	2

3.3 Feedback from students

At the Technical University of Denmark, an online evaluation system enables the student to provide feedback on the teaching methods and on their learning at the end of the semester. Over the years, the feedback received has helped reshape and improve the course, e.g. improving the course materials, reshaping the assignment structure and question formulation, putting more emphasis on challenging topics, etc.

Overall, the course has always been rated quite positively, with more than 70% of the students agreeing that "they learn a lot during the course" and "thinking that it is a good course" and with more than 60% of them agreeing that "the teaching methods encourage their active participation" and that "the teachers create good continuity between the different teaching activities". Behind these numbers, the constructive alignment of the teaching/learning activities and the real-life case studies, offering optimal hands-on practice and engagement, are largely credited by the students. On the downside, a recurrent criticism is the workload in the course, where typically more than 60% of the students feel they work more than expected for a 10-ECTS course. Besides the individual differences in managing efficiently the different tasks in the course, the case study is often demanding for the students, who are frequently thrilled by the real-life case studies and tend to push themselves – and spend extra time and efforts – into making a very good LCA report for the company.

Tracking the usefulness and impact of the course is difficult, as the contact with the students is often broken at the end of the course, but several examples over the years provide some indication of its success. After the course ends in the semester, a sizeable proportion of the students end up doing activities related to LCA as part of the continuation of their studies and/or their career. Several students thus show interest in strengthening their education in the field and seek deeper LCA training by taking other courses available at DTU that are specifically dedicated to LCI, LCIA or life cycle management (LCM). Some of them additionally find LCA an appropriate tool to address sustainability issues in their MSc thesis projects or decide to pursue specific case studies or research questions within the context of their study lines. A number of students following this path eventually become attached to the topic, and it has served as an excellent recruiting channel for later master thesis and PhD students at DTU, and former students have been seen to join the job market as LCA consultants or as LCA specialists in companies.

4 Challenges and outlooks

4.1 Assignment work

A critical aspect with regard to the assignment is their corrections and grading, which raise three distinct challenges/problems: (i) the format of the assignments as open questions, (ii) the fairness of the grading, and (iii) the plagiarism issues.

Until 2015, all assignments were formulated as open questions, which demanded important efforts from the teaching staff to correct. For example, in 2015, each of the 7 assignments required to be corrected for the 125 students within a week to provide quick feedback, in phase with the lecture topics and project work. All teaching assistants in the course as well as the course teacher contribute to the correction of the assignments, which each demands a total of ca. 50 person-hours of correction time. The workload puts important pressure on the teaching team and is not deemed sustainable if the number of students keeps increasing. Since 2015, on-line multiple choice tests (MCT) have thus been implemented to ease the correction load (the correction being done automatically by the system). Two assignments were converted into MCT. Although the correction time for those assignments has decreased, the deep learning of the students offered by the open questions was also reduced. Such loss can however be compensated by more hands-on exercises in the classroom.

Due to the increasing number of students since 2014, each assignment (excluding the MCTs) has been corrected by several persons (TAs and teachers) to distribute the workload and allow quick feedback to the students. A relative subjectivity however exists in (i) the interpretation of students' answers to open questions, and (ii) the grading of each answer. Attempts to harmonise the correction and grading have been made, using a model solution sheet and quantifying criteria for answers' correctness and completeness. Nevertheless, issues arising from students comparing results do occur sporadically, and are dealt with fairness and common sense. The way questions are formulated and the language used is another subjective aspect, which has emerged as challenging when nearly all the students and teaching staff are non-native English speakers. From the 20-year experience, several course editions are necessary to refine the questions so that they are understood unambiguously by the entire class. Finally, with the increasing use of electronic devices to support the course (e.g. on-line repository and submission of assignments), the detection of plagiarism cases have emerged. Plagiarism in the individual assignments handed in is an issue of concern. Given the diversified cultural and technical background, origins and different practices, a careful and clear explanation of what plagiarism refers to and what consequences it may have to the students should be presented in the beginning of the semester. Although the assignments are individual, we acknowledge that students do study and work on the assignment with their colleagues, friends and group mates, which is an acceptable normal procedure and strategy. However, students have to answer individually when completing their answers sheet, which is not always the case. Since 2011, we have used an automatic 'plagiarism checker' system to verify all submitted assignments against assignments from peers or from previous course editions as well as from other possible sources from the internet.

4.2 Individual learning of LCA software

Ensuring that students learn individually how to use LCA software has always been a challenge in the course. The software accessibility to the large number of students in the course has often been limited, primarily due to large expenditures and the lack of support on MAC OS X. However, as reflected in Figure 3, over the years, the LCA software learning has increasingly shifted from a group focus, where only one or two students in the groups acquired software knowledge, to an individual focus, where each student is met with LCA software hands-on practice (as part of assignment work). Although not currently applied in the course, the advent of open source LCA software, such as OpenLCA, can facilitate individual practice and learning. Over the LCA course history, investments have progressively been made to ensure that professional LCA software and databases are used so that the students become familiar with a LCA software they may encounter in their future career (either in their practice of LCA or in their reading of LCA studies).

4.3 Challenges in the handling of actual case studies by students

As discussed earlier, the real-life industrial case studies are regarded as central to the learning-by-doing process. However, the complexity of the case studies and the associated modelling work pose a challenge to students and teaching staff alike. Students should aim for completeness in their modelling, which should be sufficiently complex but as simple as possible to produce meaningful results while still be in compliance with the goal and scope of the study. It is the role of the teachers and tutors to clarify the expectations and recommend parsimony regarding the model work, as students frequently tend to directly focus on achieving a very high level of details in each part of their system modelling without discrimination in order to build an unnecessarily ‘perfect model’.

Such recommendations for parsimony are supported by the introduction to the iterative nature of LCA and the conduct of two separate iterations in the case studies run in the course. As part of the first iteration, the students are pushed to arrive at a first full product system model and set of impact results even though they have to make several strong assumptions to reach them. The interpretation of the results of this first iteration enables the groups to identify parts of the system modelling, which have the strongest influence on the results and on the answer to the question posed in the goal of the study. They can then prioritise their efforts in the second iteration of the case and thus gain work efficiency. In this process, students are additionally taught that unnecessary complexity might imply more required data and modelling effort, add uncertainty, and potentially hinder group work progress and report conclusion (e.g. due to time spent on superfluous aspects).

4.4 Implications of the increasing number of students

The increasing number of students has pressured the teaching staff to keep the alignment of structure, individual assignments and group work on real-life cases. More case studies need to be found, more TAs need to be hired, and more teacher’s time are required to correct and grade assignments and final reports, and in general to accompany the group work throughout the semester. Given that DTU does not allow putting a cap on the number of course participants and that this is in any case not desirable (to train as many future engineers and decision-makers as possible), streamlining the course has therefore become a pressing issue.

Possible alterations of the course format could include dropping the industrial case studies and adopting a ‘classic’ format of teaching lectures, or dropping the assignments and focusing on close supervision of group work and lectures. The inclusion or a final exam can also be considered for any of those options. However, these measures can only be considered as a large step backwards, as it would invalidate the fundamental pedagogical principle behind the current course design (i.e.

learning-by-doing), which has made the course as effective and popular as it is today (see Section 3.3).

To maintain and further develop the current course structure, we have identified a number of alternatives and analysed the pros and cons of each:

a) *Duplicating case studies:* Either in the same course edition or with old case studies from previous course editions, variants could be introduced by modifying e.g. the goal and scope, the LCIA methods used, the quantities and materials needed, etc. Pros: fewer companies would have to be procured; easier tutoring tasks; simplified task of report correction. Cons: higher probability of plagiarism from previous reports or from fellow students; less originality and independent thinking; weakened company contact and less student interest in the case study; increased efforts from teaching staff for managing and supplying the data (teaching staff substituting the company contact persons for older cases).

b) *Using virtual case studies or closed cases with pre-cooked datasets*: In both cases, the expected results would be available *a priori* for the teacher. Pros: fewer or no companies would have to be procured; easier tutoring tasks; simplified task of reports correction by simply checking against report solution, easier to spot mistakes and to guide students' work. Cons: intensive preparation workload to design and perform around 20 cases per year (or less if duplicated); intensive workload during the course to provide each students group with answers and data on request; less interest of the students in the case study; no hands-on experience of identifying data needs and procurement; no contact with real companies and no dissemination of LCA to these (e.g. SMEs); no confrontation with real-life challenges.

c) *Assignment work:* Implementing peer review of some assignments, replacing some others by multiple-choice tests, and changing the assignment format, e.g. by avoiding open questions, increasing calculation-based questions, and multiple-choice answers. Pros: more diversified and attractive to students; easier to correct; minimised variability. Cons: intensive workload to prepare and/or convert assignments into new formats; multiple-choice tests are meant to evaluate and not much to ensure deep learning.

d) *Lectures/theoretical background acquisition:* implementing a flipped classroom concept, in which lectures are prepared by the students before the class sessions, while in-class time is invested in exercises, Q&A, and group work (see Section 4.1). Pros: no dependency on physical space or teaching time, as students can follow online lectures on their time and location of preference; adapted to large class sizes; can provide the basis for a massive open online course (MOOC), which could be envisioned despite the teaching limitations of MOOCs as shared by Masanet et al. (2014). Cons: intensive initial workload, as all the course materials have to be adapted or prepared from scratch, like videos and other multimedia materials; concept relying on trust that the students do the preparation work (see e.g. Bishop and Verleger 2013; Herreid and Schiller 2013; Taylor 2015).

4.5 Initiating companies to life cycle thinking

The collaboration with companies around actual case studies also offers an opportunity to initiate companies to life cycle thinking. While some companies are proactive in the field of sustainability assessment and already have environmental management teams with in-house knowledge of LCA, others are not familiar with LCA and life cycle thinking in general. Their involvement in the course and the collaboration with the student groups around a case study, in which they have an interest, enables them to familiarize with the life cycle principles and understand the potential benefits that LCA can offer. This is particularly relevant for SMEs, which often do not have any resources allocated to sustainability assessment and management.

To further cater to the reality and often limited resources of SMEs, students are introduced to a screening LCA tool, i.e. the Life Cycle Check, which can be conducted with little resources and efforts. The Life Cycle Check approach is a simplified screening LCA which revolves around the building of a MECO matrix with the causing agents behind environmental impacts (Materials, Energy, Chemicals and Other aspects) and the life cycle stages as the two dimensions. It was developed as part of the EDIP project to aid Danish SMEs in their product development (Wenzel et al. 1997; Wenzel et al. 2000; available upon request to the authors). The objective of the MECO matrix is to provide the company with a crude overview of the main causes of impacts, thus enabling to identify major environmental hotspots in the system life cycle that can already be addressed by the company. Students from the course, who may become employed in companies not only bring the full LCA knowledge but can therefore also introduce the Life Cycle Check approach when resources are too scarce for a full-fledged LCA. While introducing the company to the life cycle thinking, they can thus perform a screening of the environmental profile of the company’s activities or a specific product.

5 Conclusions and recommendations

For engineers and managers to embed sustainability into their decisions and bring it to their sphere of influence, tools enabling sustainability assessment and management must be systematically integrated into engineering education programmes and be taught effectively. As one of the prominent tools for quantitative sustainability assessment, life cycle assessment should have a central place in these programmes. The experience from running an LCA course for two decades at the Technical University of Denmark is shared as a source of inspiration.

The structure of the course centred on the pedagogical principle of learning-by-doing is key to ensure effective learning by the students. The alignment of the theoretical teaching of the LCA methodology, with topic-based assignments, and, most of all, with the hands-on practice on real-life industrial case studies, has demonstrated to be essential to motivate and engage students and give them operational skills in the field of quantitative sustainability assessment. In addition, the collaboration with external companies creates a clear win-win situation for both industries and the participants in the LCA course. Students are indeed faced with all actual challenges of performing a real-life LCA study, and learn practical and pragmatic ways to overcome them. At the same time, companies not only benefit from the insights of the specific case study run in the course but also get introduced to life cycle thinking and the usefulness of life cycle assessment for their own activities. With the presentation of our experience, we therefore hope to make other LCA course teachers and companies, SMEs and large companies alike, become aware of the opportunities and benefits from collaboration.

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