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Teaching Life Cycle Assessment to Interdisciplinary Graduate Students*

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A course in Life Cycle Assessment has engaged graduate students in engineering, forestry, business administration, and public policy at the University of Washington since 2003. The course pedagogy is project-based and supported by discussion-rich lectures that provide 'just-in-time' knowledge for student projects. Project feedback is provided through three interim reports, the first describing the goal and scope of their project, the second describing and presenting their inventory analysis and the third describing their impact characterization. The final report combines these three interim reports (with responses to instructor comments), and adds the student's interpretation of the results. Students are encouraged to select projects related to their graduate research, which has contributed not only to the student experience but also to an understanding of LCA in research labs throughout the university. Although student projects are limited in scope and by simplifying assumptions, computational nuances and all steps in the LCA process are implemented.

Keywords: Life Cycle Assessment; LCA; project-based learning

INTRODUCTION

LIFE CYCLE ASSESSMENT (LCA) [1, 2] is a research protocol to assess the environmental, economic and social impacts of an industrial system. Products and processes, geographical areas, business sectors and corporations or institutions define such industrial systems. The life cycle of the system ideally extends from materials acquisition (e.g. mining, agriculture, etc.) and processing, through manufacturing, system use and maintenance and reuse, and finally through the end of the system's life (e.g. dissipation or disassembly and materials recycling, or treatment and disposal). LCA provides a method to collect, manage, and assess materials and energy information for a life cycle through four steps:

- Goal and scope definition: statement of the purpose of the study and the determination of technologies that comprise the system life cycle.
- Inventory analysis: quantification of material and energy use, recovery and waste for the technologies of the life cycle.
- Impact analysis: examination of the contribution of material and energy use, recovery and waste to impacts on the environment, economy and society.
- Interpretation: quantification and evaluation of the results of the inventory and impact assessments.

An informal survey of universities teaching LCA throughout North America was conducted in 1998 [3]. Respondents from 23 institutions indicated that LCA was being taught or planned:

1. in courses dedicated solely to LCA;
2. as a part of courses focusing on environmental considerations in business, engineering, science and public policy;
3. in courses without an environmental focus.

Just two years later, almost 50 courses using LCA at 31 North American institutions were identified through an internet search [4, 5]. In 2005, another internet search identified 54 North American colleges and universities and, as listed in Table 1, a total of 155 institutions worldwide including LCA within the curriculum. Based on this data, it is clear that LCA is becoming much more frequently taught at colleges and universities worldwide.

Table 1. Institutions including LCA in curricula

Region or Country	Number of Institutions Identified	Percent of Institutions
Europe	57	37%
US and Canada	54	35%
Japan	15	10%
Australia	10	6%
India	5	3%
China	4	3%
Africa	3	2%
Israel	2	1%
Mexico	1	1%
Republic of Malta	1	1%
Taiwan	1	1%
Thailand	1	1%
Turkey	1	1%

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Among these institutions, the University of Washington (UW) has offered LCA as a stand-alone course to graduate students since 2003. Twenty students from engineering, forestry, business administration and public policy have taken the LCA course over the past three years. In addition, to credit towards graduate degrees in Mechanical Engineering, students take the course pursuant to a university-wide certificate in Environmental Management. The course objectives are to analyse and apply the computational structure of environmental LCA and to understand the relationship between the product life cycle, environmental impact, resource conservation and pollution prevention. The course content, pedagogy, and assessment are described as follows.

UW LCA COURSE CONTENT

Since 2003, the UW LCA course content is structured around the textbook, Heijungs and Suh's *Computational Structure of Life Cycle Assessment* [1]. The textbook was originally chosen because it provides a consistent approach, terminology, and notation that based on fundamental linear algebra. Cooper [6] notes that the construction presented in the textbook has at least three advantages:

1. the method is compatible with current inventory data collection and management practices;
2. the computational structure forces the student to account for the full life cycle of material and energy flows and explicitly accounts for 'complications';
3. computational structure presented is complete in taking the student from inventory analysis through interpretation.

Table 2 presents the LCA course topics as they relate to the textbook. Notable additional topics and resources beyond the textbook in Table 2 have been added to:

1. communicate recent methodological advances;
2. introduce students to data sources and process modelling;
3. emphasize the inherent subjectivity and importance of understanding the implications of assumptions of environmental decision making.

In addition to the textbook and printed resources listed in Table 2, a very detailed class website [19] is used for course administrative including the prevision of down-loadable course lectures and links to additional reading material, and for posting the project description. Additional resources that form the basis of the course pedagogy are described as follows.

PEDAGOGICAL DEVELOPMENT

UW LCA course pedagogy was based on the 1998 North American college and university survey [3]. First, like some of the courses described by survey respondents, the UW LCA course pedagogy is project-based. Discussion-rich lectures led by the author/instructor provide 'just-in-time' knowledge and feedback for the student projects. Specifically, students prepare written interim reports throughout the 10-week quarter describing

Table 2. Discussion topics and supplementation of UW LCA class textbook

Discussion Topics	Notable Textbook Supplementation
Introduction Goal and scope definition (textbook chapter 1)	• LCA standard [2] • Specification of functional units, reference flows, and system boundaries [7] • Example assessment [8]
The basic model for inventory analysis (textbook chapter 2)	
Inventory data sources	• Inventory data sources [9] • Parametric process models in LCA [10] • Collaborative research environments [11]
The refined model for inventory analysis (textbook chapter 3)	
Advanced topics in inventory analysis (textbook chapters 4, 6, and 7)	• Allocation methods [12,13] • Cross-over time in LCA [14]
Impact Assessment (textbook chapter 8.1)	• Development of impact equivalency factors and geographic specificity in LCA [15]
Interpretation (textbook chapter 8.2)	• Numerical approaches for interpretation [16]
Extensions and implementation issues (textbook chapters 9 and 10)	
LCA Case Studies and Streamlining	• Streamlining methods and pitfalls [17,18]

the goal and scope of their project (week 2), inventory analysis (week 7) and impact characterization (week 9) of their project system which are critiqued by the instructor. Interim report content, responses to instructor comments and research findings as each project progresses are incorporated into final written and oral reports. For the final reports, students are encouraged to describe changes in interim report findings that occur during the quarter. For example, should the analysis boundaries or impacts assessed change due to insight gained or even due to time constraints, such changes are described as opposed to presented as an initial intended assessment direction.

Project selection is key to student engagement and confidently life long application of the concepts learned. Each student analyses a product or process related to their graduate thesis or dissertation, a job-related project, a personal interest, or infrequently as suggested by the instructor. Examples of student projects are listed in Table 3.

Beyond the use of a project-based pedagogy, 1998 survey respondents described methods, data sources and tools used in each of the four LCA steps. Many of the methods suggested by survey respondents have been incorporated into the lectures and discussion in the UW LCA class. First, within goal and scope definition, survey respondents noted that students are taught to choose life-cycle boundaries based on the question being asked, the product(s) or material(s) being assessed, the client, data availability, the professor's and student's area of expertise and, as described in ISO 14040 series and Canadian Standards Association guidelines. Case studies are sometimes used to illustrate boundary selection. In the UW LCA class, all these methods are discussed. Most often the final selection for student projects is based on data availability and time constraints. Although the system boundaries for student projects often do not capture important systems aspects, students are encouraged to discuss this limitation in detail.

For inventory analysis, survey respondents have students collect data by contacting companies, using databases developed specifically for life-cycle inventories [20, 21], and searching government websites and trade journals. For the UW LCA class, a website was prepared for the UW LCA class [9] listing key publicly available data websites and an inventory of other inventory sources. In 2005, students were also given access

Table 3. Examples of student LCA project topics

10-week Project Goal	Functional Unit	Basis for Project Selection
Assessment of material use and waste in the life cycle of PFSA (a Proton Exchange Membrane fuel cell membrane)	Propulsion of a 1532 kg "generic vehicle" (~4.2 kg PFSA) over 12 years	LCA MSME thesis
Assessment of the contribution of material transport to the steel life cycle	Production and delivery to manufacturing 1,000 kg steel	LCA MSME thesis
Comparison of fuel use and emissions for natural gas and hydrogen solid oxide fuel cell balance of plant designs	Provision of 40 MW of continuous power over 40 years	LCA MSME thesis
Comparison of global warming and land-use impacts for Douglas fir timber management intensities	10,305 ft^3 harvested timber at age 45	LCA PhD Dissertation, College of Forestry
Comparison of Halon 1301 alternatives FM-200 (HFC-227ea) and Intergen (Wormald Corporation mixture of Nitrogen, Argon, Carbon Dioxide)	Design concentration at which human life can be sustained (people will not die from agent if in contaminated space)	Job-related project (US Coast Guard)
Comparison of water use and contamination for virgin and recycled pulp in Korea	Production of 1,000 kg pulp	International student's personal interest
Comparisons of aircraft galley mats	Floor coverage of 12 ft^2 area over 20 years	Job-related project (Boeing)
Estimation and assessment of energy requirements for an automated sonicating machine for pathogen sample testing	Analysis of X samples per day with no occurrences of cross contamination	Non-LCA MSME thesis
Examination of the effectiveness of Dow Jones Sustainability Indexes in ranking life cycle impacts of two example companies	US$100,000 of company annual revenues	Business student's personal interest
Identification and analysis of bio-hazardous materials used in DNA analysis	Analysis of 24 samples per hour	Non-LCA MSME thesis
To examine Nike's investment in two environmental programs (Re-Use-a-Shoe and the use of organic cotton)	Investment of US$100,000	Business student's personal interest

to the Swiss Center for Life Cycle Inventories EcoInvent database [22] and were encouraged to search this data source first, followed by the preparation of a data-gaps table. Sources other than EcoInvent and the development of unit process models based on engineering principles (as in [10]) are used to fill gaps. Also, students exchange data in a collaborative web environment.

Spreadsheets were most frequently mentioned by survey respondents as a means to manage inventory data. At the UW, spreadsheets, MatLab, and Chain Management by Life Cycle Assessment (CMLCA, available for download at http://www.leidenuniv.nl/interfac/cml/ssp/software/cmlca/) developed for use with the course textbook) are used by students to manage inventory data. However, because the computational structure is based on fundamental linear algebra, most students find that basic spreadsheet functions (matrix inversion and multiplication) suffice. In 2005, students also imported spreadsheet data into MatLab.

For impact assessment, survey respondents cited environmental, resource use and economic impact categories as most frequently recommended for consideration within impact assessment. Additional impact categories include occupational and non-occupational health and safety and social welfare. Equivalency factors (or impact-specific weighting factors based on resource abundance and fate, transport and effect models) are typically used by LCA researchers and were cited as such by survey respondents. Indicators capture energy and resource consumption and contributions to global climate change, human and ecological toxicity, acidification, stratospheric ozone depletion, photochemical ozone formation, nutrient enrichment, occupational exposure, solid waste generation, water quality, oil spills and radioisotope emissions. Survey respondents cited loading assessment by impact category, equivalency factors and the Volvo-EPS-Environ-Accounting Method.

The UW LCA course uses both loading assessment by impact category and equivalency factors for impact assessment. For the latter, the students use equivalency factors from the US Environmental Protection Agency's Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) [15]. TRACI provides US regionally-specific impact equivalency factors for over 900 types of materials for twelve environmental impacts and facilitates discussion of geographical specificity in LCA. Also, the TRACI software tool allows the user to add material and energy flows and related factors. However, because the developers of TRACI have not published details of the methods used to develop the factors contained in the tool, there is no way to be sure equivalency factor additions are comparable to those contained within the software. In fact, the tool was taken off the internet before the 2005 offering of the UW LCA class with the developer noting 'at least one place where a unit conversion did not work properly' [23]. TRACI data are still used by the UW LCA class students, but discussion of the importance of methodological transparency and liability has become an important part of the class.

For interpretation, survey respondents cited the use of sensitivity analysis, probability and confidence intervals, scenario analysis, and multi-criteria analyses. In the UW LCA class, contribution, perturbation, uncertainty, key issue, comparative and discernability analyses as described in the textbook are discussed. Implementation by students typically employs Monte Carlo simulations, again within spreadsheet and MatLab computing environments.

Finally, several survey respondents cited the use of matrix and EcoIndicator methods [18, 24] as a means of minimizing quantitative data collection efforts in LCA classes. The final lectures in the UW LCA course examine the use and misuse of such tools. Specifically, students and the instructor discuss their own experiences with down-scoping due to data gaps and time constraints, frequent discussions of other simplifying assumptions and the results of interpretative analyses and how related information is lost when streamlined methods and disseminated. Finally, a detailed discussion of the subjectivity required in making a single eco-rating or decision based on multiple and often conflicting system impacts concludes the class and learning experience.

COURSE ASSESSMENT

The UW has a formal, anonymous instructional assessment system administered at the end of each course. The student evaluation includes two components:

1. a scannable evaluation form in which students rate general and specific aspects of the class from excellent to very poor or much higher to much lower and provide data related to their effort in the class;
2. a form allowing students to provide written evaluations.

Based on the former, students in the UW LCA class spend on average between 2.5 and 4.8 hours for each of the three course credits per week including classes, reading, reviewing notes and other course work which is at the high end above the UW average. They note that relative to other college classes, the course effort and involvement (assignments, attendance, etc.), effort to succeed, expected grade and intellectual challenge are much higher than average. Also, students have given scores of 'excellent to very good' for all assessed aspects of the UW LCA course.

Student written evaluations have revealed the lecture/discussion and project format facilitated their understanding of the LCA methodology and its use in the public and private sectors.

Students appreciate the availability of lecture notes on the class website. Finally, students frequently note that the project is challenging and contributed most to their learning.

Student written evaluations have suggested changes including adding discussion of economic and social analyses within the computational structure presented, adding more frequent individual meetings with the instructor and further presentation of case studies. Finally, because students in the first year of the class felt the textbook was short on examples, several were added to the lecture materials.

CONCLUSIONS

The UW LCA class provides students not only with an understanding of the computational structure of LCA but also with the ability to understand and evaluate environmental assessment results in research and professional settings. The pedagogical methods identified in the survey of those teaching LCA in North America have been used to develop this project-based classroom experience. Although student projects are limited in scope and by simplifying assumptions, computational nuances and all steps in the LCA process are implemented. Students benefit not only from their experiences in preparing their own LCA project, but also from class discussions and oral presentations by students from units throughout the University. Future additions to the UW LCA course are expected to focus on economic and social impact analysis. The growth in the inclusion of LCA in college and university curricula throughout the globe begs further discussion of related pedagogy.

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