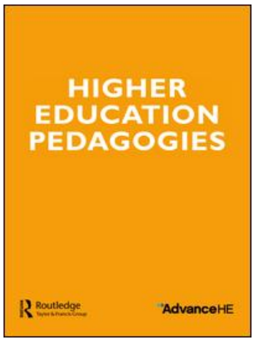
Using Life Cycle Assessment in environmental engineering education



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ARTICLE

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Using life cycle assessment in environmental engineering education

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ABSTRACT
Life cycle assessment (LCA) is a method of assessing the environmental impacts of the manufacture and use of a product or provision of a service such as waste management. LCAs are based on quantitative science, but softer skills are also required in interpreting the results. Therefore, LCA provides an ideal opportunity for students to develop and apply both quantitative and qualitative skills in order to address complex real-world problems. In this research a simplified spreadsheet LCA tool was produced for students to assess the environmental impacts of a waste management system. Detailed feedback from face to face and distance-learning students were positive about the tool, with students welcoming the detail provided in the results and the use of a practical example to help their learning. In conclusion, LCA is an effective way of encouraging environmental and engineering students to develop and apply a wide range of transferable skills.

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1 Introduction

Graduates in environmental engineering and environmental management, particularly at MSc/MEng level, need to develop knowledge, understanding and practical/professional skills in many discipline areas (Nyström et al. 2015; Richter et al. 2009). They are required to appreciate the complex interactions between chemical, physical and biological processes and understand the interactions between these processes and the environment (Weber et al., 2014). Equally important, they should have the ability to assess the financial, ethical and social implications that technologies have on the environment and be able to communicate effectively with stakeholder groups. Research on higher education pedagogy focused on employability typically concentrates on undergraduate level 4–6 provision. However, it is important to recognise the distinctive needs of postgraduates entering employment. Environmental engineering students at level 7, i.e. taught postgraduate, tend to come from an engineering or 'pure science' background and be less proficient in the social science skills. Environmental management students come from a range of backgrounds with a significant proportion from the social science traditions with less experience of the quantitative sciences.

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Therefore, all environmental students at level 7 need to gain some of the more basic skills before they can engage in the process of helping societies to develop without harming the environment (Weber et al., 2014). Most science and engineering graduates still have gaps in their scientific knowledge. For example, mechanical engineers often lack a knowledge of biological science while biologists are not always familiar with thermodynamics (Richter & Paretti, 2009). Many pure scientists need to improve their communication and negotiation skills and social scientists may need an additional grounding in mathematics, engineering, chemistry, physics and biology (Sinche et al., 2017).

As well as filling these specific skills gaps, the transition from undergraduate to postgraduate study involves providing students with opportunities to address open-ended problems without clear-cut solutions. Employers often refer to the 'professional maturity' of students in addition to specific single skill sets when commenting on the importance of recruiting postgraduates. These transferable skills for employment are commonly problem-based, focussing on the logic and reasoning of decision-making as opposed to single, correct answers as the outcome. These open-ended problems should also be industrially relevant and deal with the issues the students will have to deal with on entering employment. Many recent graduates find the change to postgraduate study to be challenging and still expect the problems they are given to have a unique, correct solution. All postgraduate teachers have needed to respond to students who ask

'but what is the right answer?'

in spite of the emphasis placed on the critical thinking and analysis skills in the teaching materials.

In this paper the discipline of life cycle assessment (LCA) is discussed, which is a widely-used method in environmental management and environmental engineering (Mälkki et al., 2017; Simonen, Moore, & Cooper, n.d.). It is also an excellent vehicle for helping students fill the gaps in their knowledge. In this context, we consider how this enhances the professional development of students enabling them to become employable environmental professionals (Richter & Paretti, 2009). Finally, LCA is ideally suited to problem-based learning activities where students become familiar with open-ended projects.

1.1 Life cycle assessment

LCA is a theoretical approach that employs a conceptual structure to assess and record the differing dimensions of environmental impact, e.g. pollution to air, land and water when predicting the overall impact of a development or process. As an environmental assessment tool, all the environmental impacts of a product or service over its entire life are quantified, hence one of LCA's alternative names 'cradle to grave analysis'. Engineering professionals are routinely tasked with determining design options that offer the minimum environmental impact during building, operation and the end-of-life phases of a project. LCA is uniquely valuable in assessing and documenting the evidence used in this decision process. Full details of the LCA process are available from a number of sources (Laurent et al., 2014; Mälkki & Alanne, 2017; Rousseaux et al., 2017), but all LCAs carried out in accordance with the international standard on LCA (ISO, 2006a, 2006b) follow the following four stage process.

Goal and scope definition – setting out the problem and why the study is being done, defining the system and what is to be included or excluded from the study (for example are the impacts of the oil industry to be included in a study on a plastic product?). Finally, defining the basis or 'functional unit' of the study (for example, the supply of one litre of carbonated water to the consumer).

Inventory analysis – compiling an inventory of all the materials and resources consumed and the wastes and environmental emissions generated.

Impact assessment – 'classification' of each substance by its effect on the environment (for example carbon dioxide and methane are both greenhouse gases while nitrogen dioxide emissions contribute to both acid rain and eutrophication, (the addition of excess nutrients, to water courses). Classification is followed by 'characterisation' where all the impacts in a given class are aggregated on a common basis (for example, knowing that methane is around 30 times as potent a greenhouse gas as CO_2 means that the impact of specific discharges of the two substances can be combined and expressed in terms of a given mass of 'CO_2-equivalent').

Interpretation – analysing the results, discussing the findings, identifying any areas of uncertainty, reaching a conclusion and presenting the results (in written and oral forms) in a format appropriate for the target audience.

At first sight, LCA is a precise quantitative method. All LCAs are built on a series of mass and energy balances that are very familiar to chemical engineering students. However, carrying out a full LCA may require the use of qualitative research methods and the results are almost always open to interpretation in several different ways. This can be illustrated by considering the debate on the relative environmental benefits and drawbacks of disposable and washable babies' nappies.

In the 1980 and 1990s around 20 LCA studies were published relating to nappies (Aumônier et al., 2005). Several of these studies were funded and/or carried out by organisations with a particular vested interest (disposable nappy manufacturers and environmental pressure groups). Whist there is no suggestion that any of these studies falsified their findings, there were questions about the independence of some of the work.

In an attempt to clarify the situation The Environment Agency (the environmental regulator for England (and at the time Wales) commissioned an LCA of nappy use (Aumônier & Collins, 2005). The work involved determining the environmental impacts of the production of the raw materials, manufacture and transport of the nappies, laundering (where appropriate) and liquid and solid waste treatment/disposal. Three scenarios were considered: disposable nappy use, cloth nappies laundered at home and cloth nappies laundered at a commercial laundry. The work drew on standard LCA databases of energy and materials production and waste management and the impacts were evaluated using some of the standard LCA categories (climate change, resource depletion, toxicity to humans and the wider environment, acidification and eutrophication). During the study it became clear that the results would be sensitive to the number of times a day nappies were changed, the way in which that nappies were laundered at home (what proportion were tumble-dried, what proportion were ironed etc.) and the age that the children stopped needed nappies. Therefore to enable the LCA to be completed, the researchers were required to commission and interpret the findings from a market research survey questioning the parents of babies and young children. This is another set of skills that pure science and engineering graduates tend not to have. The final results of the LCA showed that neither of the three scenarios could be promoted on the basis of environmental grounds. In spite of this research, the debate over the relative benefits of disposable and cloth nappies continues.

A summary of the primary skills required are defined by the authors for each stage of an LCA and are summarised in Table 1. While few students would possess all of them at the start of their postgraduate studies, they are all essential requirements of the competent environmental professional. Therefore, LCA would appear to be an ideal way of ensuring that students gain all these skills in the context of professional practice in environmental engineering and environmental management.

2 The use of LCA in higher education

A number of UK universities offer credit-bearing modules or continuing professional development (CPD) courses in LCA. Some examples being, Newcastle (10 credits, level 7), Bangor (20 credits, level 7), University College London (UCL) (CPD), Bath (6 credits level 7 and CPD), Cranfield (CPD). UCLAN (level 7), Surrey (15 credits, level 7). Many other UK higher education institutes (HEIs) teach LCA as part of other modules such as environmental management or incorporate LCA into their BEng/MEng undergraduate programmes. LCA is also taught in a number of HEIs in mainland Europe and North America as discussed below. However, the literature on using LCA in education is comparatively sparse.

The University of Surrey has been at the forefront of sustainability and LCA research and teaching and Perdan, Azapagic, and Clift (2000) discuss how the University introduced the teaching of sustainable development (SD) across its engineering curriculum. At the heart of this was the recognition that SD '*concerns a wide range of social, techno-economic and environmental issues*' (Perdan et al., 2000). Therefore, engineers have to be taught how to evaluate technical, economic, environmental and social factors. Teaching of SD begins in the first year of the undergraduate programmes and progresses so that by the third year, the use of techniques such as LCA are being taught. Central to this initiative is a series of learning resources and case studies including

Table 1. LCA skills.

LCA stage	Skills required
Goal and scope definition	Systems thinking Negotiation skills Market research
Inventory analysis	Chemistry Pollution control Transport studies Energy production Mass and energy balances Literature searching Waste management processes
Impact assessment	Environmental science Pollution dispersion Health impact assessment Ecological impact assessment
Interpretation	Critical analysis Data interpretation Presentation skills Negotiating skills

LCAs drawn from Surrey's doctoral students' research on chemical engineering and mineral processing. 16 years later, Surrey still offers MSc and PhD/EngD programmes in sustainability with LCA forming the subject of a key module in the former and the subject of many research degrees. At the undergraduate level, sustainability (including LCA) is included as a compulsory introductory chemical engineering module and is covered in a compulsory first year civil engineering module.

Chau (2007) considered some of the practical issues in introducing sustainability and LCA into the civil engineering curriculum. While recognising the need to make engineering graduates aware of sustainability, the workload required in an engineering degree leaves little scope for expansion and this was partially addressed by incorporating sustainability topics into the existing curriculum. Chau made a virtue of giving students '*… the pleasure and difficulties of having to work with uncertainties*', '*open ended problem solving*' and '*decision making based on limited knowledge*' – three concepts that are central to the work described in this paper. Chau introduced the various sustainability concepts and tools (including LCA) across a number of undergraduate modules, bringing them together in a problem-based learning (PBL) team project to design and assess the sustainability of an item of civil engineering infrastructure. Based on feedback from students, instructors and employers, Chau concluded that the curriculum changes contributed to students' understanding of sustainability, but that the PBL project alone would not enable students to develop a full understanding of sustainability without the support of the material added to the basic curriculum (Chau, 2007). The choice of material of relevance to employers then becomes an important question.

Carnegie Mellon University (USA) (Matthews, Hawkins, Jaramillo, Marriott, & Sharrard, 2009) ran an outreach scheme among high school students to promote the results of the University's industrial ecology research. In designing the programme, similar problems were faced in teaching engineering and industrial ecology to those when teaching undergraduate students; the subject has to be presented in a way that is '*student centered, collaborative and meaningful*'. An additional challenge with school students was that they had little experience of studying and solving problems that bridged the traditional discipline boundaries. A number of activities were developed to address these issues, with LCA being prominent. A typical activity consisted of the school students being presented with a real-world problem (such as reducing vehicle fuel consumption). Working in small groups mentored by postgraduate students, they selected an alternative solution, carried out calculations, developed a design and used LCA techniques to evaluate its carbon footprint. An evaluation of the scheme showed that it was an effective way if introducing industrial ecology and LCA to high school students and was also of benefit to the postgraduate student tutors/mentors. Inspection of Carnegie Mellon's website in August 2017 (Carnegie Mellon University n.d.) suggested that the scheme is no longer active and links to the resources developed are no longer live. However, the supplementary material to the online version of the paper does describe some of the activities (including an LCA activity) and provide the learning outcomes and advice to the instructors (Matthews et al., 2009). This would enable the activities to be recreated relatively easily.

LCA is widely used in assessing and improving the sustainability of buildings. However, Finnegan et al. (2013) of Liverpool John Moore's University (UK) recognised that LCA and other assessment methods are not taught on most UK degree programmes relating to the built environment. Like Chau (2007) in the case of civil engineering, Finnegan et al. stated that the best way of teaching LCA for the built environment is to integrate the subject into existing modules rather than to develop separate ones (Finnegan et al., 2013). They went on to propose a framework for teaching LCA in each year of a three-year undergraduate programme and at postgraduate level. The framework begins with teaching some of the basic concepts of sustainability and LCA at level one, working up to introducing a commercial LCA tool (Gabi) at level three and expecting MSc students to consider the use of LCA in the future and how to integrate LCA with other building information modelling (BIM) tools. The proposed framework presents a logical development of the subject, but makes no specific mention on evaluating and interpreting the results of LCAs or of dealing with the controversies raised as considered below.

Meo et al. (2014) of the University of Oklahoma (USA) also addressed the question of how LCA should be taught in higher education, in this case in the context of geography. They commented that students should gain both technical and non-technical expertise so that they could assess the policy implications of LCA results. They also noted the importance of gaining experience with LCA software. The latter presented a problem in that the intention was that students would become familiar with a commercial LCA tool, but they would not have the understanding to allow them to use LCA software aimed at engineering students. Eventually, the '*Sustainable Minds*'© software was selected (Meo et al. 2014). This is a cloud-based system and students had to subscribe to a licence at a cost of $49. The authors did not consider this a problem commenting that '*subscription fee for one semester is about the cost of an average paperback book*'. However, this would be a major issue among UK students in general and part-time/distance learning students (who are usually self-funded) in particular. In the Oklahoma module, students began by re-designing a toaster and then selected a product or process where an LCA already existed and went on to develop and assess an improved version of the product/process. After presenting the module for four years, the authors concluded that it helped students gain a clearer application of LCA thinking and that the Sustainable Minds software is suitable for students who lack a scientific or technical background.

Swinburne University (Australia) (Lockrey et al., 2013) developed a product design engineering undergraduate programme in collaboration with a manufacturer of water heating equipment. In a third year PBL module students undertook a design for environment (DfE) product to design a water heating device (kettle, shower, dish washer for example). At each stage of the design process, students were required to explore the environmental impact of their designs using a range of engineering techniques such as systems design, estimation, energy balances and carbon footprinting, Students also used the free online '*Greenfly*' LCA tool in their design and evaluations. The designs produced by the students were far more energy and resource efficient than existing products and demonstrated their application of DfE skills. Student feedback showed that they found the module challenging because there is no single 'right' answer in this area (in contrast to many design exercises). However, students viewed the module as a positive experience where they were able to demonstrate their learning and that the assessment strategy also assisted in their learning. The authors concluded that LCA allowed the students to evaluate their designs from the environmental point of view (Lockrey & Bissett Johnson, 2013).

Rio de Janeiro's Federal Center for Technological Education (Brazil) (de Souza Xavier et al. n.d.) carried out a study to assess the effects of teaching life cycle thinking (LCT) (which includes life cycle assessment) to postgraduate and undergraduate production engineering students. Modules on LCT were developed for both groups of students and students were also encouraged to undertake their undergraduate and MSc research projects on LCA themes. Postgraduate students acted as mentors to the undergraduates. In addition, collaborations were established with other universities to help promote LCA teaching and research. An analysis of the project concluded that the participating students engaged in a greater degree of reflection on sustainability in general and became much more aware of the need for greater consideration of sustainability in their professions.

3 Development of the current software tool

The software tool described here was originally developed to allow part-time distance learning students to gain an understanding and experience of LCA without the need to purchase a licence for a commercial system or to commit to the number hours necessary to train them in the use of a free version of a commercial product. As such, it is based on spreadsheets originally written for '*Microsoft Excel*' but also suitable for use with the freeware '*LibraOffice Calc*'. It was written for the UK's Open University (OU) postgraduate module on environmental monitoring and protection which is an option in the OU's Environmental Management and Engineering MSc programmes. Discussion with colleagues led to the opportunity to use the model in face to face teaching situations at two other universities.

General LCA tools can be used to model the manufacture, use and disposal of almost any product or the provision of any service. This flexibility contributes to the complexity of the tools, so the decision was taken to focus on a single activity. LCA is used in waste management to develop and improve waste management services and dedicated waste management LCA packages are available such as the UK's WRATE (Burnley, Coleman, & Peirce, 2015; Turner, Beaven, & Woodman, 2017), Denmark's EASETECH (Laurent et al., 2014) and the USA's DST (Kaplan, Ranjithan, & Barlaz, 2009). Therefore, waste management was selected for the teaching tool and this also meant that LCA could be taught in the context of an existing topic in most environmental engineering and environmental management programmes.

The model is based on results from the WRATE LCA tool developed by the Environment Agency (Burnley et al., 2015). A series of WRATE runs were carried out to assess the environmental impacts of landfill, incineration, recycling, composting, anaerobic digestion, waste collection and product transport. The results of these have been published elsewhere (Boss, 2005; Burnley & Coleman, 2012; Burnley, Phillips, & Coleman, 2012). A key simplification made in this student model was to assume that the energy produced and emissions released per tonne of waste incinerated were not influenced by the removal of any recyclable or compostable material. Whilst this will result in an error, it is unlikely to be large given that removal of recyclable and compostable waste has little effect on the heating value of the waste (Chester, 2009). Data for the distance travelled to collect residual waste, recyclables and organic wastes were taken from Burnley et al. (2011).

To allow students to consider the relationship between cost and environmental impacts, the model uses data from an extensive range of sources for processing costs (WRAP, 2012) kerbside recycling costs (WRAP, 2007), waste collection costs (Hummel, 2002) and product transport costs (DFF International, 2014).

To run the model, the students need to take a number of decisions relating to the proportions of waste segregated for recycling, composting and anaerobic digestion (biological processing of food waste to produce a fuel gas and a product that can be used to improve soil quality) and 'energy from waste' (combustion under tightly-controlled conditions to generate power for the national grid). These decisions have to be justified requiring students to gain an appreciation of the behaviour of consumers (another social science skill). Any remaining waste is assumed to be disposed of in a landfill site. The students also have to specify the waste collection frequency (weekly or fortnightly) and the distance from the town centre to the processing and disposal sites. A sample of the input screen is shown in Figure 1. It should be noted that, unlike most commercial waste LCA packages, the user cannot specify details of the materials collected for recycling or of the effectiveness of the recycling scheme. This forces the student to concentrate on the major issues rather than concern themselves with studying (say) the effect of collecting or not collecting glass for recycling.

The model uses the data on the waste management scenario specified by the user to calculate the overall life cycle burdens in terms of the six categories used in WRATE listed in Table 2 and the cost of the operation. A sample of the model outputs are shown in Figure 2–4. One valuable feature of the output (which is absent from several demonstration LCAs) is that the student gains a picture of which specific substances are responsible for the environmental impacts. In doing so students can return to the model, revise their assumptions and recalculate their results. Using these differing scenarios allows students to develop a proper understanding of the science behind environmental pollution (a new skill to some social science graduates). For example in the scenario shown, Figure 2 indicates that the principal contribution to eutrophication arises from the collection of the waste and recyclable materials and Figure 4 shows that the oxides of nitrogen (NO_x) are the main substances responsible for this. This in turn

	Inputs	
Population	200000	
Number of households	71500	
Total household waste generation	180000	tonnes per year
Landfill tax rate	64	£ per tonne
Food waste collection		
Enter coverage	80	% of area served
Enter particpation rate	80	%
Garden waste collection		
Enter coverage	95	% of area served
Enter particpation rate	90	%
Recycling collection		
Enter coverage	95	% of area served
Enter particpation rate	90	%
Energy from Waste		
Enter non-recycable waste sent to EfW (balance is sent to landfill)	100	%

	Inputs	
Incineration system	Baseline	
MRF reject rate	5	%
MRF reject destination	Landfill	
Residual waste collection	Weekly	
Distance from town to sites - enter 0 if local		
Landfill	30	km
Energy from waste plant	10	km
Compost plant	30	km
AD facility	10	km
Distance to product markets (km) - enter 0 if local		
Paper	50	km
Plastics	100	km
Glass	80	km
Ferrous metal	100	km
Non-ferrous metal	250	km
Textiles	60	km

Figure 1. Model input screen.

Table 2. Life cycle burden categories used in the model.

Category	Units
Climate change	kg CO_2 equivalent
Non-renewable resource depletion	kg antimony equivalent
Eutrophication	kg phosphate equivalent
Acidification	kg sulphate
Human Toxicity	kg 1,4-dichlorobenzene equivalent
Aquatic eco-toxicity	kg 1,4-dichlorobenzene equivalent

(The units used are standard ways of characterising emissions used in most LCA studies)

	Climate change (kg CO2-eq)	Resource depletion (kg antimony-eq)	Eutrophication (kg PO4-eq)	Acidification (kg SO2-eq)	Human Toxicity (kg 1,4-DCB-eq)	Aquatic eco-toxicity (kg 1,4-DCB-eq)
Waste collection	3 736 757	29 508	4 135	21 046	1 335 483	262 390
Waste transport	444 390	3 779	432	2 279	150 223	29 864
Product transport	462 728	5 082	626	2 897	168 091	31 481
Recycling Paper	-17 591 386	- 147 842	- 9 451	- 124 450	-4 313 632	1 085 426
Plastics	-6 912 572	- 143 281	357	- 28 130	- 71 348	- 20 176
Textiles	-12 784 165	- 100 297	- 12 486	- 92 402	-1 772 005	- 207 026
Glass	-1 017 587	- 9 386	- 1 149	- 9 737	- 800 034	- 166 674
Fe	-11 864 536	- 111 116	- 4 313	- 42 838	-3 538 161	- 313 610
non-Fe	-31 349 276	- 176 031	- 13 422	- 147 667	-165 392 944	-14 257 912
Composting	- 704 246	- 687	4 605	221	1 733 530	26 594
Anaerobic digestion	-2 944 512	- 19 907	6 401	8 377	1 071 360	135 060
Energy recovery	-12 058 970	- 227 390	2 234	- 29 579	-33 020 638	-2 873 667
Landfill	857 355	- 3 481	1 069	- 32	- 16 517	4 083
Total	-91 726 021	- 901 048	- 20 962	- 440 013	-204 466 591	-16 264 165

Figure 2. Model outputs – environmental impacts (note that negative values shown in red indicate areas where the process leads to an overall reduction in that particular category due to the recovery of energy, materials or compost).

	Cost of collection	Transport to facility	Product transport	Facility gatefee	Landfill tax	Total cost
Dry recycling	10 650 957		222 816	-2 040 714		8 833 060
Composting	2 177 747	73 872		615 600		2 867 219
Food waste AD	1 222 595	13 824		566 784		1 803 203
Residual waste collection	2 659 402					2 659 402
Energy from waste		63 063		5 171 166		5 234 229
Landfill		11 773		82 413	251 165	345 352
Total	**16 710 700**	**162 532**	**222 816**	**4 395 249**	**251 165**	**21 742 463**

Figure 3. Model outputs – financial summary.

will lead students to think about ways of improving the effectiveness of the residual waste and recycling collections and to consider ways of reducing NO_x emissions from the collection vehicles (a point with wide implications for environmental engineering and environmental management).

4 Use of the model in teaching

After its development, the model was used in a postgraduate module delivered through conventional face-to-face teaching at Cranfield University (a university specialising in post-graduate teaching and research). These are small class groups of full-time and part-time

Wate collection details

Impact	Substance	Medium	Residual waste	Recycling	Composting	AD	Total
	Tonnes collected		**66 987**	**78 489**	**24 624**	**13 824**	**183 924**
Climate change (kg CO_2-eq)	Total		1 142 153	1 926 513	427 878	240 212	3 736 757
	N_2O	Air	5 607	9 497	2 100	1 179	18 384
	Methane	Air	22 107	36 654	8 282	4 649	71 692
	Fossil CO_2	Air	1 107 121	1 869 451	414 755	232 845	3 624 171
	Unaccounted		7 318	10 910	2 742	1 539	22 509
Resource depletion (kg Sb-eq)	Total		7 369	16 404	3 673	2 062	29 508
	Coal	Resources	575	739	215	121	1 651
	Natural gas	Resources	554	856	207	116	1 733
	Oil	Resources	8 638	14 834	3 236	1 817	28 525
	Unaccounted		- 2 398	- 25	15	8	- 2 400
Eutrophication (kg PO_4-eq)	Total		1 257	2 143	471	264	4 135
	COD	Water	135	228	51	28	443
	NO_x	Air	1 088	1 852	407	229	3 576
	Unaccounted		34	62	13	7	116
Acidification (kg SO_2-eq)	Total		6 445	10 831	2 414	1 355	21 046
	SO_x	Air	2 246	3 673	842	472	7 234
	NO_x	Air	4 181	7 166	1 566	879	13 792
	Unaccounted		18	- 8	7	4	20

Figure 4. Important of NOx emissions in contributing to eutrophication impacts.

students completing a module of in-depth study whilst working with academics and external experts from industry and research. In a preliminary lecture, students were introduced to the subject of LCA, concentrating on the four stages of LCA covered above.

The students were given a copy of the model for use in an extended group project where they were asked to assess the potential for energy from waste for communities with populations of 10,000, 50,000 and 100,000 people. This design study required each small group of students to undertake a waste arising assessment for these populations, an options appraisal of waste management technologies for energy and disposal, as well as report on the most viable choice for investment. Thus the model was used for problem solving with technology choice as opposed to a single defined assignment.

The model was also used in a face to face setting on a postgraduate pollution control module at Middlesex University in 2016 and 2017. However, in this context student numbers were too low to obtain meaningful feedback from its use.

The main use of the model is at the OU in a postgraduate module taken as a core module on the environmental management and environmental engineering MSc programmes. The module is presented as part of the waste management section of the module after an introduction to LCA. The model is used in two formative exercises. In the first, students are asked to begin with a scenario where all the waste is sent to landfill and then to investigate the effects of introducing a recycling scheme determining which materials contribute most to the recycling rate and the environmental benefits of recycling. Next, they are required to investigate whether the current UK government policy of encouraging food waste digestion is environmentally justifiable. Finally, the effect of sending the non-recyclable waste to energy recovery rather than to landfill has to be determined. The second exercise is more open ended, and the students have to investigate a number of ways of achieving the government's recycling and recovery targets.

In 2017, the model was modified to take account of the feedback summarised in below and the opportunity was also taken to allow students to specify the composition of the waste they are dealing with. The modified model was used in a PBL module delivered at Cranfield, where students on the Energy from Waste and Renewable Energy postgraduate programmes were required to work in small design groups and make an environmental assessment of a system for managing the waste generated at the Cranfield campus. Again, the basics of LCA were taught at the start of the module along with other environmental assessment tools such as multi-criteria decision analysis (MCDA). The assessment of the module was based on the students' project reports (75%) and a group presentation activity.

5. Student feedback

Numbers were small in each of the student cohorts due to the specialist nature of the courses. This is typical for many post-graduate groups. However, this makes using the data for a comparative statistical analysis problematic for small-scale pedagogic studies with these groups. For this reason, the researchers sought in-depth insights from the student learning experience to then reflect on earlier work and frame the discussion.

5.1. Cranfield university (original model)

A few weeks after the students had been given access to the model a meeting was held with 10 of the students to discuss their first impressions of the model. Apart from one lecture on waste management where the model was introduced, the students had had very little experience of using LCA models. The students thought that the model was relatively easy to use, but they suggested that more information should be provided, particularly in the areas of:

- system boundaries (which sources of impacts are included);
- clearer definition of the model inputs selected by the user;
- details of the waste category composition, moisture content and calorific value (heat content).

The students were concerned about the source of the data and the assumptions made in the model. The rigour that the students rightly demand can be demonstrated by the following two quotations:

'*I've got answers, but I can't defend them*'

'*I couldn't use the CO_2 results without knowing where they come from*'.

The students would also have liked more flexibility; mainly the ability to change the gate-fee and the scope of the recycling scheme.

On the positive side the students could see how the results would help with their projects and save time. In the exercise they were set, the students had not been required to use the detailed breakdown of chemical species but thought that they would be useful later on and two students said:

'[it is] *a good teaching tool'*

'the environmental results are more detailed than [those in] *most publications*'.

Further discussions were held between the module team and the students four weeks later on completion of their projects. The students highlighted how the model had been beneficial in providing solutions to the waste management problem, but they felt that they needed to carry out more work to evaluate and defend their conclusions. This is consistent with the need cited earlier to be able to define all assumptions and relationships specified within the model. It is important to note that this group is wholly postgraduate and, as part of their assessment, would have to defend their proposals to an audience of academic, commercial and industrial representatives.

5.2 The Open University

On completion of the module's first presentation at the OU, the 24 students were asked to complete a standard feedback questionnaire which had the addition of three specific questions relating to the LCA model. Replies were received from 12 students, (7 based in the UK and one each from students living and/or working in Norway, Denmark, Malaysia, Kenya and Georgia).

When asked if the model helped them understand the role of LCA in making environmental decisions, nine responded positively, two did not answer that question and one simply replied 'no'. The latter student explained in a later comment that they were not prepared for the technical and mathematical content of the module. Some of the positive comments included

'I generally always find that use of something in a practical example helps reinforce learning'

'It made me appreciate how changing small things like how we recycle our waste or introduce a composting scheme can have a large effect on the outcome of our waste management schemes on the environment'

'I had studied LCA in [a previous module], *but the model introduced a good method to classify impacts*'

Eight students also said that the model helped them understand the concept of integrated solid waste management (a key message of the module). Again, two students did not reply, one simply said 'no' and one noted that they could not be certain because they had to rush through that part of the module (it was presented in the final weeks before the examination).

Finally, the students were asked for suggestions on how the model and its use could have been improved. Six suggestions were received. Some referred to clarifying an ambiguity in the associated assessment question and this was done. Other suggestions included:

adding screenshots of the model to the module material;

providing more maths and science preparatory material (this was done);

linking the model to the waste hierarchy (another key concept in waste management covered by the module).

5.3. Cranfield university (campus model)

The students were provided with a group-based assignment to appraise options to enable the campus to become self-sufficient in terms of energy consumption. To do this the groups assessed various sources of low-carbon energy, such as solar, wind, biomass and wastes produced by those working and living on the campus. The LCA model was provided to the groups, along with a demonstration in class and a brief lecture on the principles of LCA. This enabled the groups to learn about the application of LCA in a real-life context, and to apply the model to assist them in their assignment.

The students were given one week in which to work together in their groups and formulate a solution for the campus. Their findings were presented and discussed with the whole class and the tutors contributing to the module. They then had a further two weeks to complete an individual technical report of their findings. Feedback was sought from the groups following their presentation at the end of the first week.

When asked '*did the LCA model help you to understand LCA?*', 100% of the responses were positive. In response to '*did you use the LCA model in your group project?*' the responses were mixed, as were the responses to '*did the model help you in developing your plan for the campus?*'. It is likely that, whilst the students felt that the LCA model was of value, the groups were restricted in the time allowed for the assignment. Thus, they prioritised their workload and many were not able to implement the LCA model into their work. This is most likely to be the waste-focus of the model, with the groups looking at other energy options in parallel with waste. Therefore, tasks were distributed among members of the group and so some members were not involved in assessing the waste-related options.

Further feedback of the LCA model requested that it be adapted to include wind and solar energy options. This feedback further supports the conclusions that members of the groups were not looking at technology options suitable for this specific LCA model, but that all group members saw merits in understanding LCA.

6 Discussion and conclusions

The professional requirements to complete an LCA in many engineering contexts offers a valuable opportunity to introduce evidence-based decision making within the curriculum. The tool is widely applicable in predicting the environmental impacts that are likely from using a product or service. Whilst the majority of engineering professionals will engage with LCA at some point understanding the process and use of LCA results at an early stage is important. Students across many disciplines need to develop and use a range of scientific and technical skills in an integrated manner. However, results from LCA studies tend not to be clear cut. LCA practitioners need to engage with a breadth of subjects including environmental ethics, systems thinking, stakeholder consultation and, above all else, develop good communication skills. These 'softer' skills are often under-developed in many engineering and science students and thus engagement through the application of LCA helps them develop this expertise in a professionally relevant educational setting. Practical reinforcement of conceptual ideas is a direct and traceable process. This is notable when interpreting results as an LCA requires a sound understanding of the underlying science behind the generation of the environmental pollutants and on the technology relating to pollution abatement. This integration of scientific evidence within a decision-making process is challenging for students from any discipline. It is also characteristic of professional experience in employment where detailed analysis needs is used and leads to evidence-based decision that records critical judgement. In Higher Education pedagogy opportunities to relate conceptual ideas with an evidence base in a professional context delivers a powerful learning experience. The case example here of LCA providing environmental management students from a social science background with an incentive to acquire 'harder' skills shows evidence of this synthesis within the learning task. In summary, LCA with its need for a multi-disciplinary approach and lack of clear-cut answers, provides an ideal source of PBL activities at postgraduate level while providing the students with valuable practical and employability skills.

There are many commercial LCA tools available and some universities make use of them. While they are ideal for use by PhD students (and possibly for use in MSc research modules) they do have a number of drawbacks when used in taught modules. Acquiring the skills necessary to use any particular software package takes time. Providing this training, can really only be justified in a module dedicated to LCA because environmental management and environmental engineering modules tend to be content-heavy and can only teach the basic concepts of LCA along with other essential concepts. Therefore, in this situation, commercial LCA tools are less helpful than a bespoke tool such as the one described here.

Furthermore there can be cost issues with commercial LCA tools. Some are available in demonstration versions, but are not suitable for project work and others require a licence fee. If the student is required to pay for a licence, the payment must be justified through maximising the use of the tool – again a problem in the more general environmental modules. It is also difficult to ask students for additional payments on top of their fees (many students are self-funded) while many universities would find it impossible to fund licence fees from their resources.

The development of the spreadsheet-based LCA tool described in this paper allows students to undertake project work in a waste management context on LCA without the time and cost implications of using a commercial system. The model only needs limited input data to be selected to allow the user to generate and assess realistic waste management scenarios.

The model has now been used in distance learning teaching the OU for five years and in face to face teaching at Cranfield and Middlesex twice.

Feedback from the Cranfield University students was wholly supportive in its use and they appreciated the model as an aid to understanding the environment impacts of waste management. During the first presentation, students asked for more details respecting the system boundaries and the sources of the data used. This was provided in the second presentation.

Student feedback from the Open University was more mixed than that of the Cranfield students, but was still generally supportive, with the majority of the students stating that the model helped them to appreciate LCA and integrated waste management. A number of suggestions for improvements were suggested; these have all been incorporated into the model or will be added to the teaching materials during its next revision.

In conclusion, the development and assessment of this LCA model has demonstrated that LCA can be taught in a practical way at postgraduate level. Furthermore LCA can be used as a means of teaching many key environmental and engineering concepts and introducing students to the uncertainties present in real-world problems.

Disclosure statement

No potential conflict of interest was reported by the authors.

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