Paper 69. Educational Principles for Engineering Education for Sustainable Development: Experiences from the U.K. and Canada

Susan E. Nesbit[1], Heather J. Cruickshank[2] and John C. Nesbit[3]

[1]Department of Civil Engineering, University of British Columbia, Canada.

nesbit@mail.ubc.ca

[2]Department of Engineering, University of Cambridge, UK.

[3]Faculty of Education, Simon Fraser University, Canada.

Abstract

In what ways do the pedagogical practices in engineering education for sustainable development align with and diverge from principles derived from educational research and current theories of motivation, cognition, and learning? How can these principles and theories guide the development and implementation of new programmes in engineering sustainability education?

The *MPhil programme in Engineering for Sustainable Development* (www-esdmphil.eng.cam.ac.uk) at Cambridge University has been in operation since 2002 and has graduated over 320 students. The *undergraduate Civil Engineering program at the University of British Columbia* has offered a course entitled "Engineering and Sustainable Development" since the 1994 and is now supported by its University Sustainability Initiative (www.sustain.ubc.ca). This paper describes examples of pedagogical practices used in these two programmes, including cohort-based learning and service learning, and offers lessons learned from the teaching of engineering-for-sustainability. Further, it relates the teaching and learning experiences of sustainability within these two engineering schools to evidence-based educational theories that refer to cognitive, motivational, and social aspects of learning. Based on this analysis, instructional principles for designing and implementing new programmes in sustainable engineering are presented.

1 Introduction

Late 20th century academic, public, and professional, discourse about sustainable development has precipitated calls for change in both engineering practice, and engineering curricula (for example, see Carroll, 1993; Forum for the Future (1996); Beder, 1998; World Federation of Engineering Organization, 2001; Institute of Civil Engineers; 2003). Acknowledged in these calls are the imperatives of sustainability (Robinson, 2004) and the need to develop sustainability attributes in graduating students, including attitudes of openness to complexity, uncertainties, and respect for perspectives of "others" (for a contemporary description of these general attributes, see Teaching and Learning Office, U.B.C., 2013). The attitudinal nature of this knowledge challenges engineering educators to develop and apply novel learning activities that augment student development of the traditional engineer's stance.

Many engineering schools have responded to this call. For example, the MPhil in Engineering for Sustainable Development at University of Cambridge (MPhil ESD), first offered in 2002, was built on the Department of Engineering's prior experience with the Royal Academy of Engineering's Visiting Professor scheme, which it joined in 1999. The one-year full-time professional practice programme was initially funded through the Cambridge-MIT Initiative and targeted young engineers with some work experience who wanted more formal training in the broader concepts of sustainable development in a form that could be applied in their jobs (Cruickshank and Fenner, 2012). Based on what Ove Arup called the 'T-shaped' engineer, the course assumes a significant level of technical depth (the 'vertical' of the 'T') in its students who come with a strong first degree in engineering or a related technical subject, and aims to provide the business breadth (the 'horizontal') to that experience. In essence, the MPhil teaches students to ask better questions.

Another example of the academy's reaction to early calls for sustainable development in engineering education is the undergraduate civil engineering curriculum at the University of British Columbia Canada (CIVL UBC) in which a core 2nd year course entitled "Engineering and Sustainable Development" was first introduced in 1994. Since 2007, a sustainability learning framework has been developed where-in core integrated project courses are "book-ends" for a suite of sustainability technical electives. A purpose of the first (2nd year) book-end course is to introduce the broad notion of sustainability as part of professional development to in-coming students which they revisit in their graduating year as they work through applications of their technical knowledge to an open-ended infrastructure design project for a municipal client.

Independently of engineering education, a multifaceted educational research enterprise with roots in the early years of the 20th century has accelerated to the point where many evidence-based principles of learning and pedagogy can be articulated (Winne & Nesbit, 2010). The research supporting these principles consists of thousands of observational or experimental studies that each assessed a link between an instructional practice and subsequent learning outcomes (Hattie, 2009). The principles range from relatively macro-level descriptions (e.g., "Prior knowledge can help or hinder learning.") to more specific instructional prescriptions (e.g., "The difficulty level of instructional tasks should match student's ability."). The psychological theories that inform the principles deal with motivation, cognition, individual differences, self-regulated learning, and socio-cultural factors.

2 Research Questions and Methods

The knowledge accumulated through education research raises intriguing questions for educators of engineering for sustainability, including:

1. In what ways do the pedagogical practices in engineering education for sustainable development align with (and diverge from) principles derived from educational research and current understanding of motivation, cognition, and learning?

2. How can these principles guide the development and implementation of enhanced or new programmes in sustainability engineering education?

This paper reports the outcomes of a retrospective reflection stimulated by these questions. Notable changes in the MPhil ESD and the CIVL UBC programs are interpreted through the lens of relevant educational principles. Possible implications for engineering sustainability educators are presented.

3 Reflections and Discussion

3.1 Changes in Engineering Education for Sustainable Development: MPhil ESD and CIVL UBC

Some of the current characteristics of the two programmes (described in Table 1) have changed since they were first offered and we observe that while the programmes have evolved independently of each other, many of the curricular and pedagogical changes are similar. For example:

1. Sustainability engineering topics have moved from the 'more-general' to the 'more-specific'.
   Students in both programs are no longer introduced to broad definitions of sustainable development, or the phenomenon of climate change. Instead, students are introduced to aspects of systems theory, industrial ecology, resilient and regenerative infrastructure, supply-chains, and global/humanitarian engineering. Within each topic, applications, opportunities, and examples are learned at varying depths, depending on whether the students are undergraduates or graduates.

2. Learning activities aimed at developing professional attitudes that are consistent with sustainability values have become more explicit.
   Both informal (MPhil ESD) and formal (CIVL UBC) reflection exercises are clearly aimed at leadership aspects of professional development, particularly as it pertains to understanding one's personal beliefs and comparing one's beliefs to others.

3. Community-based team projects, which have always been part of both programmes, have become more focused on student interests.
   The MPhil ESD Management of Technology and Innovation (MoTI) projects have shifted from a business and enterprise focus engaged in by students from across the university to MoTI projects whose clients are ESD MPhil alumni, and the projects now have a clear sustainability engineering focus. The CIVL UBC Community Service Learning (CSL) projects offered to undergraduate civil engineering students at UBC have changed from being broadly related to sustainability (for example, a project related to planning sustainable food production) to being clearly embedded in civil engineering context (for example, a project related to planning for sustainable water treatment and conveyance infrastructure).

4. Classroom learning activities have shifted from faculty-led activities toward student-directed learning.
   For example, in the CIVL UBC program, several lectures from experts have been replaced by panel discussions involving experts at different scales (e.g., policy, city planning, engineering), who consider questions posed by students. Also, instead of faculty members leading small group discussions, students are trained to plan and lead

structured small group discussions on topics of their choosing. In the MPhil ESD program, students are now tasked with identifying and investigating their own projects, rather than relying on faculty members to present case studies. Also, in-class learning activities are sometimes "flipped" such that, instead of lectures, students view on-line videos then come to class prepared to engage in small group discussions.

Table 1: Characteristics of the Sustainability Engineering programmes offered at the Universities of Cambridge and British Columbia.

Programme Characteristic	MPhil in E.S.D., U. of Cambridge	CIVL B.A.Sc., Sustainability Learning, U.B.C.
Programme Goals	Theme of "breadth"	Theme of "professionalism"
Length of Programmes	1 year	3 years
Learning Time	4 courses per term plus thesis - all learning activities are focused on engineering sustainability	Up to 6 courses out of 36 - engineering sustainability learning activities are interspersed with traditional engineering education
Student Age	~26 years old	~20 years old
Student Professional Experiences	All with undergraduate degree from any engineering or related discipline, and most have previous professional experience. Some may be chartered engineers.	No professional experience. Approximately 10% of the cohort may have previously worked as a civil engineering technician. All students are in the civil engineering discipline
Learning Activities	Lecturing, Role-plays, field trips, workshops, projects, thesis	Lecturing, Expert Panel Discussions, Student-Led discussions, reflection journals, mapping of systems
Team-based Projects	Course Assignments	Community Service learning (CSL) Projects, Course Assignments
Projects for Community "clients"	The Management of Technology Innovation (MoTI) module; MPhil Dissertation	CSL Team project in 2nd year, Capstone team project in 4th year (for municipality or other local authority)
Peer mentoring	Students are encouraged to discuss their personal professional (and other) experiences in class and often self-organise mutual support groups as required.	Senior students mentor 2nd year CSL teams, CSL team members submit summative evaluations to team mates, students provide peer feedback to discussion leaders.
Cohort Learning	Students are full-time residents of the city, take core classes and many electives together, engage in significant extra-curricular sporting and social activities (approx. 40 per cohort)	B.A.Sc. Students take 24 core courses together over a 3 year period, two of which are the Sustainability Learning framework "book-end" courses. (approx. 125 per cohort)

As a result of these changes, we observe that more students engage in discussions and explore deeper questions in their written work. Further, students appear to develop self-efficacy and are able to articulate the value of knowing the perspectives of others. We also observe that, while some students (particularly the CIVL UBC students) continue to express frustration with the "messy" nature of the community-based project experiences, they are now interested in developing management strategies aimed at finding solutions to open-ended problems as part of their professional development. Finally, it seems that students are more comfortable in taking responsibility for their learning.

3.2 Educational Principles Related to Learning Engineering for Sustainability

The curriculum and pedagogy changes described above reflect a variety of evidenced-based principles of teaching and learning.

Aligning learning activities and assessments with learning goals

An overarching principle of instructional design is that learning activities and assessments should align with intended learning outcomes or goals. The shift from lectures by experts to panel discussions with experts in the CIVL UBC program aligns that learning activity with the goal of being able to use sustainability engineering knowledge to persuade, question and give explanations to others involved in a project. Compared with listening to lectures, observing how experts respond to questions and even how fellow classmates pose them, is better preparation for taking on similar roles as discussants in project meetings. The shift from faculty-presented case studies to student-directed investigations in the MPhil ESD program is a re-alignment of the learning activity to match more closely with what students are expected to do after completing the project.

Small-group learning

A review that aggregated research on over 5000 undergraduates learning science, technology, mathematics and engineering (Springer, Stanne & Donovan, 1999) found small group learning was associated with higher academic achievement, greater commitment to completing a task, and more favourable attitudes relating to the subject and the learning experience. On all these dimensions, small-group learning outperformed whole-class learning by an average of approximately 0.5 standard deviations. It may be that the increase in discussion participation and interest in exploring questions observed in both programs is a result of increases in the number of small-group learning activities.

Social cognitive modeling

Observational learning, which can occur in any social setting, is a fundamental psychological process that underlies small-group learning and many other instructional methods. When a student observes a model such as an instructor or peer performing a skill or expressing a belief, the probability that the student learns the skill or belief depends on a variety of factors such as the perceived competence of the model and the perceived similarity between the model and student (Bandura, 1986). The revised teaching methods in the two programs (e.g., expert panels, small-group problem solving and discussion) appear to have introduced increased opportunities for observational learning.

Self-explanation

Of the many ways to structure small group interactions, most involve students giving explanations to others. Research on undergraduates studying a variety of subjects has found that generating explanations deepens the knowledge of the explainer and promotes academic achievement (e.g., Chamberland et al., 2011). Pedagogical changes in the programs (e.g., introducing reflection exercises and the small group activities) prompt students to generate relevant explanations and may therefore result in greater understanding of engineering sustainability concepts.

Conceptual change

A goal of both the CIVL UBC and MPhil ESD programs is changing students' attitudes and beliefs toward both sustainability and the role of the engineer in sustainable development. However, one of the difficulties of bringing about profound change in students understanding and attitudes is the retention of prior misconceptions and beliefs alongside the newly acquired knowledge (Dole & Sinatra, 1998). Research has found that if, in addition to acquiring new ideas, students are exposed to arguments that directly refute prior misconceptions, they are much more likely to retain the newly acquired knowledge over the long term and use it in future decision-making. An implication for sustainability engineering education is that class activities should be structured to promote critical thinking and reasoned debate about sustainability issues so that uninformed assumptions can be examined and perhaps refuted.

4 Implications for Engineering Educators

4.1 Pedagogies of Engineering for Sustainability

This paper emphasizes a challenge for engineering educators raised by the need to embed engineering for sustainability into both graduate and undergraduate engineering education. We contend that facilitating student development of sustainability attitudes, beliefs, and values is a significant aspect of engineering education for sustainable development. Educational principles suggest that the following instructional activities may best address this challenge.

- Multiple Opportunities for Social Modelling
  It may be that the more students observe sustainability role models, including practicing engineers, senior students, and peers, the more students are able to envision the enactment of sustainability attitudes, beliefs, and values.

- Argumentation aimed at enhancing critical thinking skills
  Employing an argumentation framework to explain their thoughts, and to critique the thoughts of others, may be a useful vehicle by which critical thinking is increased. This framework can be used to explore newly acquired sustainability knowledge and previously held misconceptions.

- Small group learning activities
  Small group learning activities, carefully structured to reflect the maturity level of the students, can facilitate the development of sustainability attitudes, beliefs, and values via social modelling (i.e. observational learning) and argumentation.

- Opportunities for personal reflection
  The three reflective steps of articulating new ideas, explicitly connecting this new knowledge to previous experiences, and receiving feedback on this expression, may support student reconceptualization of their prior knowledge.

3.4 Advancing Engineering for Sustainability Education

To advance engineering sustainability education, novel teaching methods need to be discovered and disseminated. It may be that *design research* (or design-based research), characterized by successive modifications of plans and practices contributing to the creation of robust instructional designs and perhaps generalisable learning models (Collins, Joseph, & Bielaczyc, 2004), is a useful approach. Similar to some forms of engineering practice, the essential idea of design research is to use progressive, repeated refinement of design to drive discovery. Both build on a necessary foundation of empirically validated theory that is always insufficient to understand fully the interactions between their designs and the environments in which those designs function (O'Neill, 2012). In educational settings, the intended design is never exactly what is experienced by learners because so many unaccounted for variables intervene between conception and actuality. Repeatedly implementing, attempting to explain outcomes, and accordingly refining our instructional designs may be the most direct and amenable method for attaining valid theories and effective practices in sustainability engineering education.

By describing a cycle of re-designs common to at least two engineering-for-sustainability programs, and by using educational principles to account for some of the outcomes of those designs, we have realized aspects of design research but have not implemented two crucial features. First, we have not collected and analyzed the detailed data (i.e., student academic performance, focus group discussions, etc.) that is necessary to support an accurate description of how students responded to the design changes in the two programs. Second, we have not articulated a model of how students learn in the programs that could be used to predict their response to further refinements in program design. Implementing these practices in our educational research may offer the best prospects for advancing engineering education for sustainable development.

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