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Not all Constraints are Equal: Stewardship and Boundaries of Sustainability as Viewed by First-Year Engineering Students*

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The overall purpose of this research was to research attitudes and threshold concepts (key concepts or gate keeper concepts) of beginning engineering students towards the relationship between environment/ecology and engineering specifically towards choosing: either (a) engineering as a career to make an environmental impact or (b) choosing environmental and ecological engineering as a specific engineering profession. The project was situated in the context of life cycle analysis and the environmental impacts of design, manufacturing, use and disposal of products. The study employed also an innovative research design: The researchers investigated students' conceptions and attitudes (and change of both) by asking students to co-design an educational game with them—through a series of workshops. Of particular focus was the change of students' conceptual understanding of core environmental and ecological concepts during the design process. First, we reported the results of a survey of 1437 first-year engineering students at the Purdue University, West Lafayette campus. The survey tested student knowledge of environmental issues, their prioritization of sustainable development in various contexts, and also explored student attitude toward change. We observed positive correlations between the high school science courses or high school environmental education, and the average environmental knowledge scores. There was no difference in average knowledge scores when comparing male and female students. In addition, we reported the results of an analysis of students' data as collected within the workshops. Second, we reported on preliminary findings on the participatory design workshops (n=24). The study revealed several areas of 'troublesome' knowledge of students.

Keywords: sustainability; environmental engineering; resistance to change; first-year students

1. INTRODUCTION

IN ITS REPORT entitled 'The Engineer of 2020: Visions of Engineering in the New Century', the National Academy of Engineering (2004) reported by the year 2020 'the world's population will approach 8 billion people' [1]. Not only will urban areas and developing nations experience significant increases in population centers, populations found in these areas will place considerable demands on the world's natural resources. The tension between ever-increasing global populations with decreasing availability of natural resources provides the engineering community with substantial opportunities for the development of meaningful solutions addressing environmental issues.

One of the most pressing issues faced by local and global citizens is that of environmental education. How do we educate current and future citizens about the preservation and management of natural resources? The value and importance of environmental education has been endorsed both in the United States and internationally (e.g. [2]). Despite this, 'two-thirds of adult Americans consistently fail simple tests of environmental knowledge' [3].

It could only be imagined, how much high school and beginning college students know about environmental and ecological engineering and are aware that engineering is a very viable career choice for

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students who want to make an environmentally and ecologically sustainable impact.

The following examples demonstrate that engineering skills and knowledge are essential to environmental protection and enhancement. First, would a person switch from a standard residential home to an 'energy efficient home', if s/he knew that the carbon footprint, use of energy, and greenhouse gas emissions of constructing the home were substantial compared to the energy consumed while residing in the home? Consider another example: If one already owned a mobile phone, how to quantify the impact of upgrading the phone every year or two? The growing number of electronics devices do not harm the environment during use, but their lifetimes are so short and there are so many of them that disposal is an issue.

The questions embedded in these scenarios are not just for the individual end user; the questions aim at the core of engineering and highlight that the design, manufacturing, use, and disposal of products, in short the product life-cycle, has an equal if not higher impact on the environment than end users' actions.

2. OBJECTIVES OF THE STUDY

The objectives of this study were to research the attitudes and threshold concepts (key concepts or gate keeper concepts) of beginning engineering students towards the relationship between environment/ecology and engineering, specifically towards choosing either (a) engineering as a career to make an environmental impact or (b) choosing environmental and ecological engineering as a specific engineering profession. The project was situated in the context of life cycle analysis and the environmental impacts of design, manufacturing, use and disposal of products.

The study was theoretically grounded in (1) 'social cognitive career theory' (SCCT) and the (2) theory of 'threshold concepts' (TC). SCCT maintains that people's interests in certain careers stem partly from their self-efficacy (beliefs about personal capabilities) and outcome expectations (beliefs about the outcomes of engaging in particular courses of action) [4, 5, 6]. TC argues that there are key concepts that change the way in which students view a discipline [7]. This study researched students' change of attitudes and conceptions especially in regards to outcome expectations (as defined by SCCT), meaning: how well did students understand that their environmental/ecological impact was extremely high by choosing an engineering career and which concepts seemed to be 'threshold' concepts?

This study addressed the following questions:

- What is the knowledge level of first year engineering students in regards to environmental and ecological issues, in particular environmental engineering?
- What are threshold or gatekeeper concepts, which helped students to transform existing knowledge into deeper conceptual understanding?
- What is the baseline conceptual understanding of ecological and environmental engineering and life cycle assessment?

The study employed also an innovative research design: The researchers investigated students' conceptions and attitudes (and change of both) by asking students to co-design an educational game with them. Of particular focus was the change of students' conceptual understanding of core environmental and ecological concepts during the design process.

The expected outcome of this study: A better understanding of students' attitudes and threshold concepts towards environmental engineering and a baseline to design new interventions to support a stronger view of engineering as a career for positive environmental impact.

3. LITERATURE REVIEW

3.1 Conceptions and attitudes of engineering students towards environmental and ecological issues

Through documentaries like 'An Inconvenient Truth' and other venues, public awareness on ecological and environmental issues increased in the last years. Available data in reports such as, 'Environmental Literacy in America: What 10 Years of NEETF/Roper Research and Related Studies Say About Environmental Literacy in the U.S' show mixed results: On the one hand, the report shows a 'confused public that performs poorly on basic environmental literacy questionnaires', on the other hand '95% of this public supports environmental education in our schools' [3].

Earlier work on environmental literacy in the field of engineering showed a similar pattern amongst engineering students: In a worldwide survey amongst engineering students, Azapagic et al. (2005) [8] found (a) unsatisfactory knowledge, and at the same time (b) a general belief that environmental issues were very important. Although reports exist in the engineering education literature, especially on individual lesson design [9] and curricula design [10], there is a gap in the literature and a general lack of more detailed research into the conceptions and attitudes of students towards environmental and ecological issues, especially how both relate to engineering careers.

3.2 Threshold concepts and attitudes

Conceptual change is among the conceptions of learning that have recently been most closely embraced by the educational psychology and learning sciences communities [11]. Humans natu-

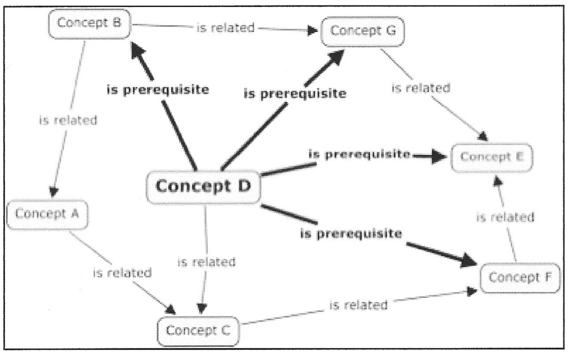

Fig. 1. 'Concept D' as a threshold concept.

rally build simplified and intuitive theories to explain their surroundings. The cognitive process of adapting and restructuring these theories based on experience and reflection is referred to as conceptual change. Most research indicates that conceptual change arises from interaction between experience and current conceptions during higher-order cognitive activity, especially when cognitive conflict arises [12]. Cognitive conflict or 'troublesome knowledge' [13], however, is not always sufficient for engaging conceptual change. Students often ignore, reject, exclude, or reinterpret anomalous data or they hold them in abeyance [14], which is largely due to beliefs and attitudes [11].

The new emerging theory of threshold concepts [7] argues further that there are hierarchies within concepts, in which certain concepts are threshold or gatekeeper concepts. Attributes of threshold concepts are (a) transformative (transforming the understanding of a domain), (b) irreversible (change of perception is unlikely to be forgotten), (c) integrative (exposes other relationships), (d) bounded (context-specific) and (e) troublesome (counter intuitive) [7].

As depicted in Fig. 1, 'concept D' is such a threshold concept, meaning if concept D is not understood properly, it is most likely that concepts B, G, E, and F will not be properly understood, since concept D is the prerequisite for these other concepts. Given such complex and concept-rich domains as in engineering, threshold concepts become increasingly important: Results of 'threshold concept' research can inform teachers and administrators on where to set priorities and allocate resources to maximize impact on students' learning.

3.3 Participatory design

As stated, the study used participatory design of a game as one of its design features. Törpel (2005) stated 'participatory design of computer applications is about the direct participation of those who will be affected by the development of a particular computer application in the decision-making, design and/or development process' [15]. In this proposed project, students were collaborative co-designers of an educational game from which other students would benefit. The concept of participatory design, used primarily in product design, has long roots in educational design and research practice as well [16, 17, 18].

Stemming from a constructivist paradigm [19], the role of computers as 'mindtools' or 'cognitive tools' was emphasized: meaning to utilize the computer as a partner for the intellectual and social endeavors of the learners rather than utilizing the computer as a glorified teacher [20]. As Jonassen et al. (1993) reported, instructional designers learned far more by designing CAI (computer-assisted instruction) than the target audience would probably ever learn by using the designed CAI [21]. Both concepts argued for a reciprocal relationship between learners and content, and highlighted the notion of 'designers as learners' and 'learners as designers'. Additionally, as the rich teach-back literature [22] showed, learners were especially successful when teaching newly acquired knowledge and skills to other learners.

4. METHODS

The research team utilized the theoretical frameworks of participatory design-based research, comparative design-based research, and threshold concepts and attitudes, as the basis for this research project. This framework is depicted in Fig. 2 and provided researchers with:

- A novel way to elicit students' attitudes and conceptions (especially threshold concepts) about ecological and environmental engineering.
- The opportunity to ensure that end-users were actively involved throughout the game design process, so end-user needs and expectations were met.
- The ability to pinpoint students' threshold/gatekeeper concepts concerning ecological and environmental engineering, informing teachers and instructors where to set priorities and allocate resources to maximize impact on students' learning..

The research team continually reviewed overall research goals, provided participants with feedback, and monitored interactions between members of the study participants and the research team. The research team implemented these processes in order to maintain quality and consistency throughout the game design process. Baseline data analysis, participants call-out and selection and resource support provided sufficient inputs and the process phase consisted of preparation work, data encoding and decoding.

4.1 Instruments

The research team developed a web-based survey tool, which created a unique key for each student. The survey instrument contained Likert-

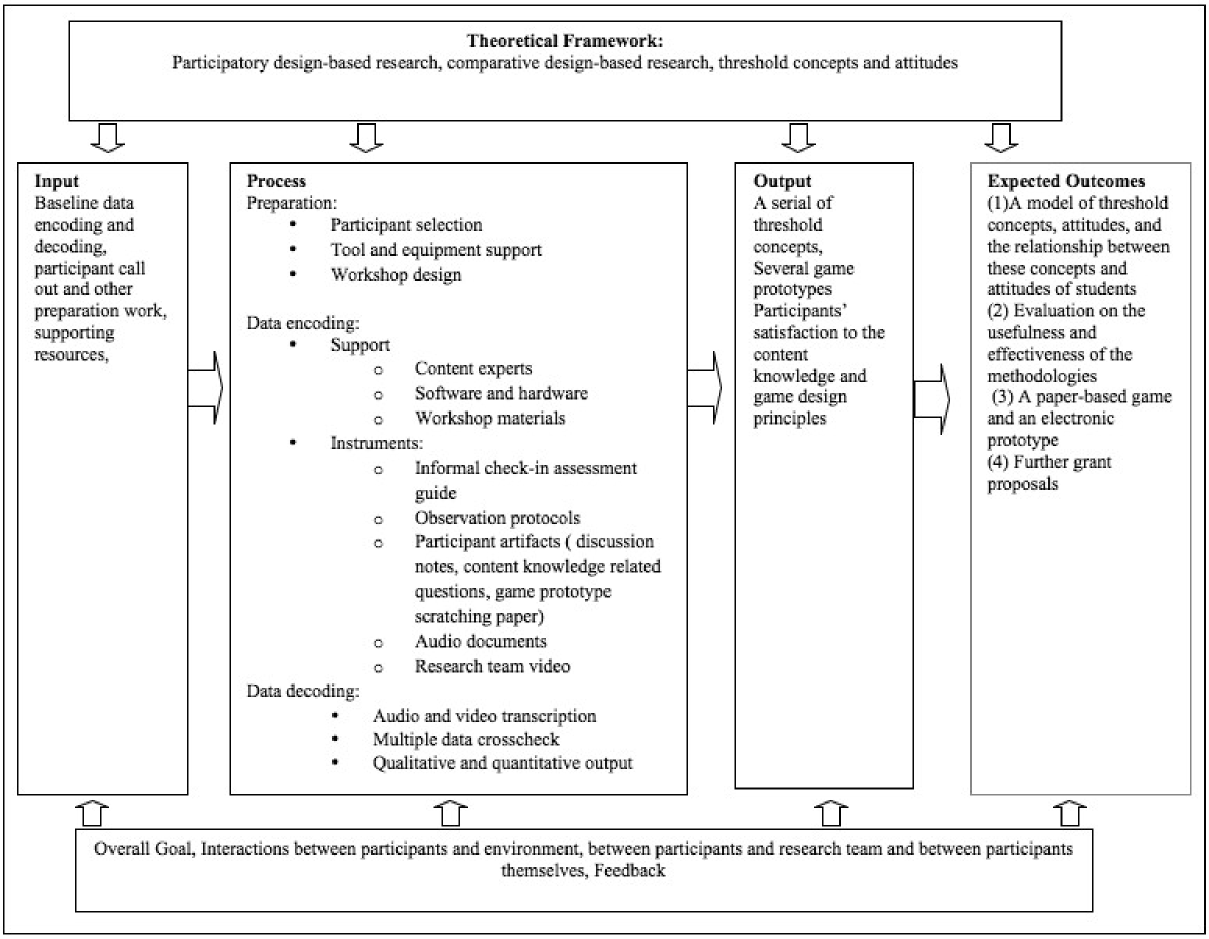

Fig. 2. Research logistics conceptual framework

scale questions (0 = Not heard of to 3 = Know a lot) asking students to rate their own knowledge of (1) environmental issues (such as acid rain, photochemical smog), (2) environmental legislature/policy, (3) environmental engineering technology and (4) sustainable development. In addition, students were asked to rate the importance of sustainable development in various contexts (for themselves, for their profession, for their country, etc) and also explored student attitude toward change. Students were also asked whether they had environmental education in high-school. This question was followed-up with two open-ended questions asking them to describe the environmental education they had and the education they would have liked to receive in high school. The survey was constructed by adapting an existing survey instrument, the environmental engineering instrument [8].

The research team developed four (4) workshops, hosted a wikispaces environment, and designed two (2) online activities. The game design workshops provided a venue in which study participants could interact amongst themselves, as well as be observed by research team members. The wikispaces facilitated team member communication. The online activities supplemented information presented in the face-to-face workshops. Research team members also used the workshops to develop observation data, collect team artifacts, such as drawings, and reflections. The research team also provided student teams with assistance when needed during the workshops.

The themes of the workshops varied corresponding with the research process. The first workshop focused on Life Cycle Assessment (LCA) content knowledge. The content knowledge included describing the phases of a complete LCA (goal and scope definition, inventory analysis, impact assessment, and interpretation) and the notion of functional units. In addition, several case studies were presented that highlighted how LCA results could be included in design decisions, including an LCA of computer monitors and an LCA of a residential home. Students were also provided with the abstracts of approximately 25 LCA case studies. Research team members also presented an overview on game design principles. The second workshop began with a review of LCA and was centered on game design model and principles. The third and fourth workshops were structured as 'working sessions'. Each team used their workshop time to develop game prototypes and provide one another with peer evaluation.

4.2 Survey and preparation phase

The research team administered the survey encompassing student demographic information, as well as their initial understanding of ecological and environmental engineering, as a basis for selecting student participants. The survey included various competencies within the field of environmental engineering, including pollution control and remediation approaches, as well as regulations. The return rate was n = 1437.

For the purpose of avoiding bias and increasing reliability and validity in the data collection process, participants of the second and more in-depth research components, were selected based on the following rules:

- Prospective participants were recruited from the students enrolled in ENRG10000, which was the beginning engineering course for all first year engineering college students.
- Students taking courses of the professors in the research team were ruled out.
- A stratified sampling strategy was utilized so that each participant team had a mix of demographic background.
- Six teams of 4 students were recruited for the game design workshops.

4.3 In-depth design and data collection phase

After the initial survey provided the research team with baseline data and the individual workshop teams were selected, the data collection phase for the qualitative and participatory component started. The duration of this phase was seven months (Survey collection: August 2008; Workshops: November 2008—February 2009). The research team used a multitude of data sources when triangulating study data (Fig. 3). The data collecting process was centered on a series of game design workshops, which consisted of four face-to-face workshops and two online activities. Six (6) teams of four (4) students participated in the workshops and various instruments were utilized to collect data.

As previously mentioned, the research team introduced LCA content knowledge during the first workshop. Participants were then encouraged to answer five (5) questions highlighting basic knowledge of LCA, such as their personal definition of LCA and their own understanding of environmentally friendly products. These five questions served as the basis for the research team check-in assessment, and were presented in an informal manner to the research subjects. The research team structured this activity in such a way to alleviate participant stress. Once the participants answered these five questions, their answers, reactions, and initial attitudes regarding environmental/ecological engineering and documented and analyzed.

During each workshop, the research team also implemented an observation protocol. This protocol was intended to document participants' reaction, attitudes, and the extent to which participants understood the LCA content knowledge and game design principles. Research team members also collected paper artifacts, such as team notes and outlines and drawings. During the team meetings, the research team deployed audio recording devices and recorded team conversations, such as prototype brainstorming. Research team members gathered after every workshop section and videotaped their opinions of the strengths, weaknesses and suggestions of each workshop section.

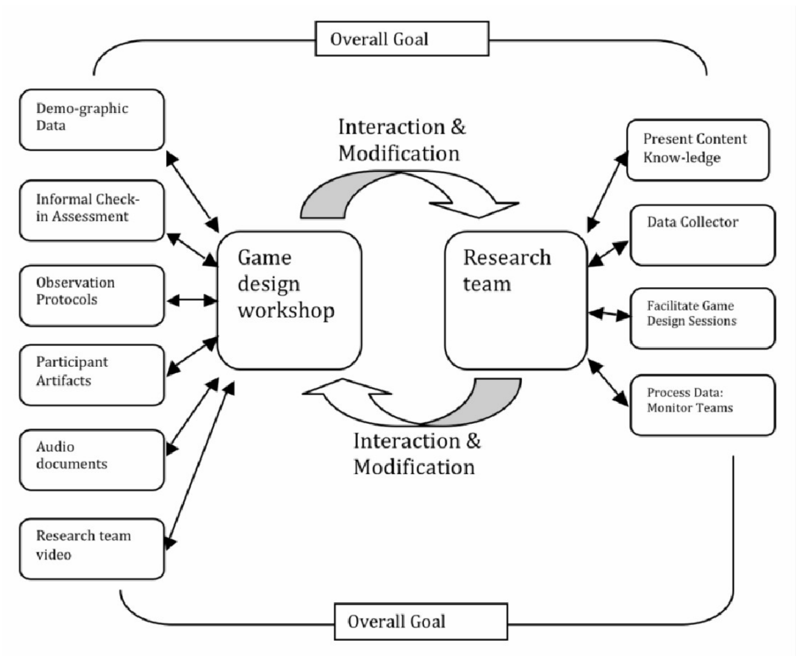

Fig. 3. Data encoding model.

Challenges of data collection

1. Loss of some participants threaded the consistency of team participation and the final project. Due to the small size of each team, a 2 or 3 person loss from one team, which is quite normal for research, resulted in combining two teams together after the first workshop.
2. It was hard to keep the gender balance, as there were much fewer female students in the college of engineering.

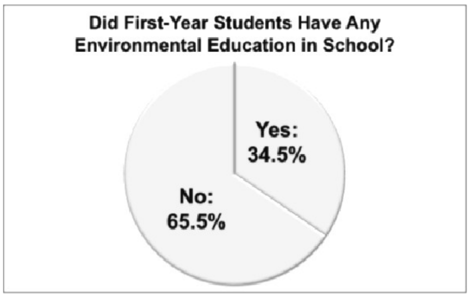

Fig. 4. Environmental education.

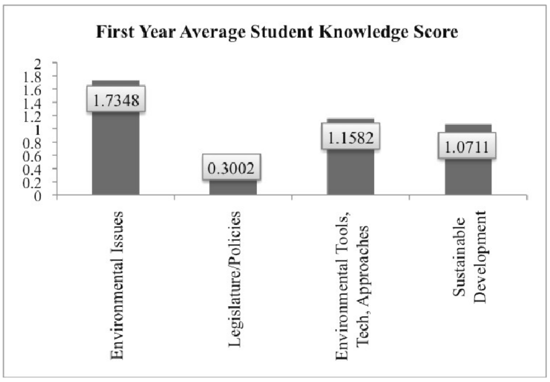

Fig. 5. Knowledge on environmental issues.

5. RESULTS

5.1 Survey data

The following data are based on the survey (n = 1437). Two-thirds of the first-year students indicated that their high school experience did not include any environmental education (Fig. 4).

As Fig. 5 shows, First-Year students demonstrated a much higher knowledge level in the category of 'environmental issues', which included acid rain, water pollution, air pollution, global warming. Students demonstrated less knowledge in environmental tools, sustainable development, and legislature and policies governing environmental issues.

Items in the 'environmental issues' category are frequently in the news media or are topics which do not need much specialized information to understand such as 'water pollution'. So it could be argued that the less common the terminology, the more specialized prior knowledge was required to understand the concepts, and therefore the least likely students were aware or knew about the particular environmental issue. In other words: students' awareness of environmental challenges was much higher than knowledge on how to take up these challenges.

Correlating the research results of Fig. 4 (Environmental education in high school) with research results of Fig. 5 (knowledge in environmental engineering issues), the research team compared the average knowledge score in each category of environmental issues for students who answered 'Yes' versus students who responded with 'No' on environmental education. The comparison is shown in Table 1. Students received environmental education in high school did indeed demonstrate statistically significant higher scores in all knowledge categories.

Pearson correlations (two-tailed) were calculated for the range of cumulative semester hours of high school math and average score in each of the four categories of environmental knowledge, or for the range of cumulative semester hours of high school science and the average score in each of the four categories of environmental knowledge. Information about specific math or science courses (e.g., trigonometry versus calculus, biology vs. chemistry) was not available.

The range of cumulative semester hours of high school math was 0–16 with an average of 7; the range of cumulative semester hours of high school science was 0–19, with an average of 9. Correlations were declared significant at the 0.01 level or the 0.05 level.

The number cumulative semester hours of high school math is not positively correlated with

Table 1. The correlation between high school environmental education and students knowledge of environmental issues (N=1360)

	Semesters of high school math taken	Semesters of high school science taken	Prior environmental education
Prior environmental education	–	–	–
Semesters of high school math taken	–	–	–
Semesters of high school science taken	0.268**	–	–
1. Environmental issues	–0.101**	0.180**	0.272**
2. Legislative policy	–0.069*	0.123**	0.196**
3. Environmental tools, technologies, approaches	–0.028	0.103**	0.096**
4. Sustainable development	–0.70**	0.155**	0.161**

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

student scores in any category of environmental knowledge. However, the number of semesters of high school science is positively correlated with student scores in all categories of environmental knowledge. A cautious interpretation would indicate that typical high school science courses include chemistry, biology, and physics and therefore could possibly include case studies or examples related to the environment.*

5.2 Gender differences

Given the greater participation of women in environmental engineering degree programs (as mentioned earlier in this paper), the researchers explored gender as a factor that may impact environmental knowledge scores. The data were subject to Levene's Test for Equality of Variances. In all cases, there was no significant difference in the knowledge scores of male and female first-year engineering students.

5.3 Qualitative results

The following research questions relied on non-numerical data and produced non-numerical answers and so a qualitative research framework were chosen to analyze and represent the results: (1) What are threshold or gatekeeper concepts, which help students to transform existing knowledge into deeper conceptual understanding? (2) What is the baseline conceptual understanding of ecological and environmental engineering and life cycle assessment?

The following themes emerged by analyzing the non-numerical data. The research team employed a grounded theory approach, which included open coding (applying key phrases to all textual information) and axial coding (grouping of the key phrases to larger units for the purpose of synthesis and reduction). Quotation marks indicate direct quotes of the students' statements.

5.4 List of conceptual domains in which threshold concepts were embedded

A variety of qualitative data resources were examined, generating themes reflecting students' understanding and attitudes towards environmental issues. The themes were categorized into a list of conceptual domains in which threshold concepts were embedded. The conceptual domains provided a summary of all the concepts that students felt most frustrating and critical. The domains represented students' central concerns on LCA content knowledge of the collective case and are as following:

- *Domain 1: Measurement units and techniques.* Students felt that a comprehensive understanding of the functions of measurement units and techniques was key to the understanding of LCA. There is some ambiguity in the phrase 'measurement units,' and the research team interprets the meaning of the phrase to be conversion between units of measure of physical quantities related to environmental impact (possibly quantities measured in the inventory phase of an LCA).
- *Domain 2: Capabilities and application of LCA.* Students felt frustrated about what LCA was able to do and how each LCA step functioned. Students showed great interest in how LCA related in daily life.
- *Domain 3: Assessment methods/tools.* Students discussed assessment methods/tools involved in the LCA process.
- *Domain 4: Energy consciousness.* Students showed great concerns over energy consumption and incorporated energy consciousness as one of the primary topics in their game prototypes.

While these domains provide us with a target area, in which to extract and discover threshold concepts, this research is too preliminary to declare specific threshold concepts. However, this research can describe in more detail troublesome knowledge, which students encountered. As described earlier, threshold concepts share several different attributes, one of which is to be troublesome, meaning that threshold concepts—once encountered—challenge existing patterns of thinking. In the next section, we describe particularly troublesome knowledge extracted from the non-numerical data (observations, design artifacts and interviews).

5.5 Results of LCAs are surprising and 'troublesome'

During the workshops, the students read, interpreted and discussed a variety of different LCAs, which the research team selected. From the verbal and non-verbal reaction of the students, the research team was able to conclude, that results from the LCAs were surprising for students and made them question their previous conceptions. This was particularly observed when students encountered counter-intuitive aspects of LCAs.

5.6 Compromising functionality for environmental concerns

Students felt comfortable talking about their perception of engineering, as a domain, which thrives for optimal or best performance and functionality. They expressed that the particular focus on LCA would mean that 'functionality is made secondary' or that they would have to 'only think of the environment', which students expressed as a

* Since this article is written for a dual audience of (a) engineering education researchers and (b) faculty in other technical engineering fields, a note about 'statistical significance' might be warranted: First, statistically significant correlation does not imply causality. It merely describes strength of the linear relationship between variable x and y. In social science research, correlations like the ones found in our study are considered moderate. In other words, social science research does usually not produce statistical correlations in similar strength to engineering research. By researching the complexity of any human system, we rarely know most of the variables let alone correlations between them.

puzzle or contradiction to their understanding of engineering. The LCA is perceived as a borderline engineering related task. The researchers did not see much evidence that environmental issues are perceived as a required component of what makes a product 'functional'. A different version of the same argument surfaces, when students express that LCAs are more valuable for end-users and less valuable for engineers ('convince someone that one product is more ecologically friendly than the other [. . .] and trying to persuade them that buying a greener car is better').

5.7 'Just information'—no means to tell how to act

Students were quick to determine, that to measure the environmental impact of a 'course of action' or 'process', 'merely gives you quantifiable results for a certain action', but the LCA itself was perceived as not providing a roadmap, courses of possible actions nor even options for a decision ('by no means does it tell you what to do'). Also it was acknowledged that it needed to be decided 'which factors are most/least important'. Students understood LCA as a sophisticated form of analysis, yet they showed little understanding that the LCA was part of a larger picture within an engineering process, a starting point for creativity or problem solving. The LCA was perceived as an unrelated or stand-alone event in regards to other forms of engineering such as design or development.

5.8 Cradle to cradle or cradle to grave—how it is made

A small number of students expressed that a LCA was connected to the larger process of making products ('the most important aspect of LCA is actually how a product is made', yet 'it is hard to explain energy/fuel cost in production of products [emphasis by student]. The emphasis on the production was particularly seen in the context of 'decomposing a product', so individual components could be addressed to decrease the environmental impact of a product).

5.9 Intertwined process—Uncertainty and less-optimal-data-environments—no single component alone

LCAs are highly complex and much data, assumptions, and analysis are invested to create LCAs. For some students the most troublesome component for LCAs was the complexity. This showed itself either in realizing (a) the LCA alone had many components: 'they are all multi-faceted; there is not one factor alone that determines whether a product or method is better' (b) that producing a LCA report required 'a compilation of multiple tests', (c) concerns about the accuracy of the analysis 'understanding how the tests were done and under what circumstances so you can accurately interpret an understand the numbers' and no clear cut answer of how to trust the results, and (d) a feeling of being overwhelmed with the amount of knowledge and information which is needed 'I really don't know all of the raw materials used in making a product'.

6. SUMMARY AND CONCLUSIONS

In its first step, this study revealed trends across a large body (n = 1437) of first-year engineering students at an R1 university: Students across the board were aware of environmental issues, yet when it came to specific legislature, environmental engineering tools/approaches and sustainable development strategies, students' awareness and knowledge were considerably lower.

In the second part of the study, the research results of the qualitative study (n = 24), revealed interesting components of students' conceptual understanding of LCA and its relationship to engineering. Particularly the artificial separation between functionality and environmental friendliness of a product and the difficulty of students to connect the results of LCA to the larger engineering process gave insights into difficulties and troublesome knowledge of students. While this study revealed troublesome knowledge, which challenged the students' existing thinking, the study is only preliminary in its definition of threshold concepts.

Findings contribute to the small body of existing research in environmental engineering education research. In the next phase, particularly the qualitative findings need to be further studied by transforming them into a valid survey to be employed over a large body of students. A cross-institutional approach is also considered as a next step.

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