Use of Concept Maps to Assess Student Sustainability Knowledge

Dr. Mary Katherine Watson, The Citadel, The Military College of South Carolina

Dr. Mary Katherine Watson is currently an Assistant Professor of Civil and Environmental Engineering at The Citadel. Prior to joining the faculty at The Citadel, Dr. Watson earned her PhD in Civil and Environmental Engineering from The Georgia Institute of Technology. She also has BS and MS degrees in Biosystems Engineering from Clemson University. Dr. Watson’s research interests are in the areas of engineering education and biological waste treatment. Specifically, she has been involved in research projects to develop, refine, and apply innovative assessment tools for characterizing student knowledge of sustainability. Her ultimate goal is to use this assessment data to guide the design and evaluation of educational interventions to improve undergraduate sustainability education. In the area of bioprocessing, Dr. Watson has experience using bacteria and algae to convert waste materials into high-value products, such as biofuels.

Mr. Joshua Pelkey, AirWatch

Joshua Pelkey is currently a product manager at AirWatch in Atlanta, GA. He completed his MS in Electrical and Computer Engineering at GT and his BS in Computer Engineering from Clemson University. He has conducted research and lead design projects in a variety of fields, including mobile device management, wireless communications, and remote monitoring of environmental systems. Joshua has been very interested and well-versed in sustainability issues since his tenure as an Engineers without Borders member and webmaster at Clemson.

Dr. Caroline R. Noyes, Georgia Institute of Technology

Caroline Noyes is trained as an educational psychologist, and her education and work have focused on assessing student learning both in and outside of the classroom. Experiences in both academic affairs and student affairs provide her with a holistic understanding of the modern university and a broad collection of assessment methodologies suitable to a variety of situations. As her intellectual pursuits turned increasingly towards broader applications of educational assessment and evaluation, she left the classroom and moved to an administrative position focusing on both academic assessment of student learning and program evaluation. This administrative move has allowed her to increase use of qualitative assessment methods, and to enhance her skills in survey design.

Dr. Michael Owen Rodgers, Georgia Institute of Technology

Dr. Michael Rodgers is a research professor in the Georgia Tech School of Civil and Environmental Engineering and a principal research scientist and distinguished technical fellow with the Georgia Tech Research Institute. Over the last thirty plus years, Dr. Rodgers has held various academic, research and administrative positions including serving as director of the Georgia Tech Air Quality laboratory from 1988 to 2008. He currently serves as deputy director for Research and Technology Transfer for National Center for Transportation Productivity and Management at Georgia Tech.
Use of Concept Maps to Assess Student Sustainability Knowledge

Introduction

Sustainable Development

Sustainable development has emerged as a promising strategy for combating un-sustainable patterns of population growth, resource consumption, poverty, and environmental degradation. The most widely accepted definition of sustainable development, published in Our Common Future in 1987, states that sustainable development is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. The outcome or goal of sustainable development is to create a sustainable society, which is “one that can persist over generations, one that is far-seeing enough, flexible enough, and wise enough not to undermine either its physical or its social systems of support”.

Furthermore, the 2002 Johannesburg Declaration proposed the three pillars of sustainable development to be economic development, social development, and environmental protection. Economic sustainability requires that a development maintain or improve economic welfare, while environmental sustainability dictates conservation of natural resources. A project is socially sustainable if it improves social equity and provision of services. Many organizations and academic authors have since endorsed a sustainable development paradigm and the three-pillars framework.

Sustainability and Engineering Education

Although technological innovation has contributed to current unsustainable practices, engineering is important for developing and implementing sustainable development strategies. However, for sustainable engineering to effectively contribute to global sustainability, engineering curricula must be updated to properly train sustainably-conscious engineers. Current curricula emphasize disciplinary specialization and reductionist thinking. As a result, many graduates are “unbalanced, over-specialized, and mono-disciplinary graduates” who use their narrow skill sets to solve problems by analyzing system components in isolation. In contrast, the complex nature of global and local dilemmas necessitates that sustainable engineers exercise interdisciplinary and systems thinking to understand and balance the interrelated technical, economic, environmental, and social dimensions of a problem. For instance, alleviation of global problems of resource scarcity and environmental degradation in the context of population growth requires a broad knowledge base and the ability to analyze problems holistically. However, a committee commissioned by the National Academy of Sciences
(NAS) posited that tackling complex global dilemmas will “challenge” the skills and creativity of traditionally-trained engineers.\textsuperscript{16, 17}

Recognizing the potential benefits of sustainable engineering, many organizations have called for curricular reform. For instance, the Accreditation Board for Engineering and Technology (ABET) requires that students possess “the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.”\textsuperscript{18} Furthermore, the American Association of Engineering Societies (AAES) state in their cannons of professional conduct that “engineers shall hold paramount the safety, health and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties.”\textsuperscript{19} Clearly, there is great interest in integrating sustainability into undergraduate engineering education.

To effectively design and evaluate the effectiveness of such educational reforms, accurate and reliable tools for assessing student sustainability knowledge are needed. Most commonly in the literature, student sustainability knowledge is characterized using indirect student perceptions surveys.\textsuperscript{20} While such tools can provide a rough characterization of student knowledge, direct assessments often provide a more complete picture of student knowledge.\textsuperscript{21} In particular, concept maps (cmaps) have been identified as unconventional, yet promising, tools for capturing student knowledge of a given domain, including sustainability.\textsuperscript{22-25}

\textit{Project Scope}

The goal of this paper is to demonstrate the use of cmaps for assessing student sustainability knowledge, to ultimately aid in the design and/or evaluation of strategies for incorporating sustainability into engineering curricula. A case study was conducted to quantify the sustainability knowledge of civil and environmental engineering (CEE) seniors at the Georgia Institute of Technology (Georgia Tech) using cmaps. Specifically, this study addresses the following research questions: (1) What do scores suggest about the balance, connectedness, and overall quality of CEE student sustainability knowledge? (2) Are there any differences in sustainability knowledge between civil and environmental engineering majors? (3) What insights can cmaps provide for the design of educational interventions to improve student sustainability knowledge? Overall, results will be used to guide assessment and reform efforts in CEE at Georgia Tech and abroad.
Literature Review

Sustainability Knowledge Assessments

Effective methods for assessing student sustainability knowledge are needed throughout the process of transforming an undergraduate curriculum or course. First, assessments are needed to characterize student knowledge to properly inform the design of educational interventions. For instance, if students simply have no prior knowledge about sustainability, then strategies are needed to help students “add” sustainability knowledge to their repertoire\(^\text{26}\). If students have accurate, but incomplete, knowledge of sustainability, then educators can help students “fill the gaps”\(^\text{26}\). For the case of missing and incomplete knowledge, instructors can guide students in “enriching” their knowledge\(^\text{26}\). However, the fourth possibility is that students have misconceptions related to sustainability that must be corrected\(^\text{27}\). In this most extreme case, conceptual change is required, which can be relatively difficult for educators to facilitate, depending on the level of misconception\(^\text{27, 28}\). Once an appropriate intervention strategy that reflects the nature of students’ preliminary knowledge is developed, then assessments are again needed to verify the effectiveness of and continuously improve the instruction.

Hence, assessment is critical for designing and evaluating strategies for improving student sustainability knowledge. An ideal assessment task is objective and reliable, minimally influences student responses, and reveals knowledge structure\(^\text{29}\). Traditional assessment instruments, such as multiple choice or standardized tests, inherently restrict student responses and provide little insight into knowledge structure, although they are usually very objective\(^\text{30}\). As a result, objective tests may be unsuitable for assessing sustainability knowledge because they do not allow students to reflect on the inherently broad content and interrelated structure of sustainability. Open-ended assessment methods, such as essays and presentations, are usual alternatives to objective tests that disclose more about knowledge structure, but are often accompanied by subjective scoring rubrics that are difficult to apply\(^\text{30}\). In addition, student inability to produce acceptable artifacts (e.g. reports or posters) may be mistaken for lack of knowledge in the domain\(^\text{30}\). Consequently, traditional open-ended assessments may be unfeasible for broad and accurate sustainability assessments. Due to the shortcomings of traditional objective and open-ended assessments, more innovative tools, such as journals, annotated portfolios, and concept maps (cmaps), have been suggested for more accurately capturing student knowledge in a particular domain\(^\text{21}\).

Concept Maps

Concept maps specifically may be a useful tool to assess student knowledge. These theoretically-supported constructs allow students to freely reveal the content and structure of
their knowledge. Thus, cmaps are appropriate for examining sustainability knowledge, as evidenced by published literature.

1. Concept Map Components

Cmaps are graphical tools for organizing knowledge. Construction of a cmap is completed by enclosing concepts related to a central topic in boxes and using connecting lines, as well as linking phrases, to depict relationships between concepts. The basic unit of a cmap is a proposition, which includes two concepts joined by a descriptive linking line. Propositions that include the cmap topic define the map hierarchies, while the level of hierarchy is defined by the number of concepts in the hierarchy. Cross-links, which are important for representing concept connectedness, are descriptive linking lines that create propositions by joining two concepts from different map hierarchies (Figure 1). Cmaps have been used in educational settings as a learning strategy, an instructional method, a curriculum planning guide, and an assessment tool.

![Figure 1. Cmap hierarchies and cross-links](image)

2. Theoretical Basis for Cmaps

Use of cmaps is supported by cognitive psychological research in the area of semantic memory theory. Semantic memory refers to an organized database of concept-based knowledge, such as meanings, understandings, and images. Unlike episodic memories, semantic memories contain factual knowledge about the world that is not temporally-dependent. Semantic memory theory posits that knowledge networks are formed by creating directed links between related concepts. Some researchers have proposed that networks are structured hierarchically with broad concept categories being divided into more specific sub-categories (Ausubel’s hierarchical memory theory), while other researchers have rejected this assumption (Deese’s associationist memory theory). Nevertheless, interconnectedness within the structure is an important network
characteristic, since it increases one’s ability to access concepts and is a key feature that differentiates expert and novice knowledge frameworks\textsuperscript{32,37}. Since cmaps mimic the structure of internal semantic networks, student-generated constructs may be used to infer a student’s domain understanding\textsuperscript{37}. In fact, the cognitive validity of cmaps has been previously evaluated and confirmed\textsuperscript{38}. Thus, using cmaps in the classroom can provide students with an opportunity to articulate and evaluate their semantic memory networks, while providing instructors with a tangible construct to aid in evaluation of a particular knowledge domain.

3. Scoring Techniques

For cmaps to provide the desired insight into student knowledge, appropriate methods must be used to process the rich data into a form that can be easily analyzed. Two scoring methods that are useful for analyzing the content and structure of student knowledge reflected in cmaps are traditional and holistic methods. In the traditional method, the number of concepts, highest hierarchy, and number of cross-links are counted as indicators of knowledge breadth, depth, and connectedness, respectively\textsuperscript{21}. The total score is then computed by summing the three sub-scores using appropriate weightings (Table 1). Alternatively, the holistic method prompts judges to use a previously-validated rubric to rate the comprehensiveness, organization, and correctness of cmaps on a three-point scale\textsuperscript{21}, with the total score being computed as the sum of the three sub-scores (Table 1).

<table>
<thead>
<tr>
<th>Method</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>\textsuperscript{39} Total = (NC-NCL) + (HH)*5 + (NCL)*10</td>
</tr>
</tbody>
</table>

Specific for sustainability-related cmaps, the categorical method \textsuperscript{25} is an alternative scoring approach. This method directs judges to classify each concept according to a ten-category taxonomy (Table 2) to aid in calculation of metrics (CD\textsubscript{i,j} or CR\textsubscript{i}) that describe the topics that students most associate with sustainability (Table 3). In addition the number of inter-links, or connections between concepts from different categories, is quantified to aid in computation of an overall complexity index (CO\textsubscript{j} or CO\textsubscript{cohort}) (Table 3). A review of these three methods, including evaluation of reliability and validity as sustainability knowledge assessments, is available elsewhere\textsuperscript{40}. 

---

\textsuperscript{39} Example reference for the traditional method.

\textsuperscript{21} Example reference for the holistic method.

\textsuperscript{25} Example reference for the categorical method.

\textsuperscript{40} Example reference for the evaluation of reliability and validity.
Table 2. Examples of concept categorization based on ten sustainability categories [Adapted from Coral\textsuperscript{41} and Segalàs et al.\textsuperscript{25}].

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>pollution, degradation, conservation (of wildlife), biodiversity, ecological footprint, green/clean</td>
</tr>
<tr>
<td>Resource (scarcity)</td>
<td>renewable/non-renewable resources, lack of materials, energy, food, water</td>
</tr>
<tr>
<td>Social Impact</td>
<td>quality of life, health, risk management, shelter</td>
</tr>
<tr>
<td>Values</td>
<td>ethics, awareness, respect for traditions, judgments about sustainability</td>
</tr>
<tr>
<td>Future</td>
<td>future generations, scenario analysis, forecasting, backcasting</td>
</tr>
<tr>
<td>Unbalances</td>
<td>equity, fair distribution of goods, fair use of resources, needs of developing countries</td>
</tr>
<tr>
<td>Technology</td>
<td>best available technologies, industry, efficiency, clean-technologies, impact of technology, technological efficiency</td>
</tr>
<tr>
<td>Economy</td>
<td>role of economy, fair trade, consumption, economic efficiency</td>
</tr>
<tr>
<td>Education</td>
<td>role of education, rise of awareness, educational institutions</td>
</tr>
<tr>
<td>Actors and Stakeholders</td>
<td>role of governments, rules, laws, international agreements, politics, individuals and society</td>
</tr>
</tbody>
</table>

Table 3. Categorical metrics used to score cmaps [Adapted from Segalàs et al.\textsuperscript{25}].

For an individual student $j$:

- **Category Analysis**\textsuperscript{a,b}:
  $$ CD_{i,j} = \frac{\sum_{i=1}^{NS} NC_{i,j}}{\sum_{i=1}^{NS} NC_{i,j}} $$
- **Complexity Analysis**:
  $$ (L_{Ca})_{j} = \frac{NIL_{j}}{N_{Ca}} $$
  $$ (L_{Ca})_{avg} = \frac{\sum_{j=1}^{NS} NIL_{j}}{N_{Ca} * NS} $$

For a cohort of students:

- **Category Analysis**\textsuperscript{a,b}:
  $$ CR_{i} = \frac{\sum_{j=1}^{NS} CD_{i}(\frac{NS}{NS})}{\sum_{i=1}^{NS} CD_{i}(\frac{NS}{NS})} $$
- **Complexity Analysis**:
  $$ (L_{Ca})_{avg} = \frac{\sum_{j=1}^{NS} NIL_{j}}{N_{Ca} * NS} $$

**Variable Descriptions**

- $CD_{i,j}$ = concept distribution displayed for category $i$; $NC_{i,j}$ = number of concepts included in category $i$; $(L_{Ca})_{i}$ = Relative number of inter-links between concepts from different categories; $CO_{i}$ = category $i$ relevance; $NS$ = number of students including concepts from category $i$; $NS$ = total number of students in cohort; $(L_{Ca})_{avg}$ = average relative number of interlinks for cohort; $CO_{cohort}$ = cohort-specific complexity index; $NC_{avg}$ = average number of concepts for cohort.

\textsuperscript{a}Ten-category taxonomy employed Segalàs et al. \textsuperscript{25}: environment, natural resources, social impacts, values, temporal, spatial, technology, economy, education, and stakeholders.

\textsuperscript{b}Modified from Segalàs et al. \textsuperscript{25}: Environmental mega category: environment + natural resources; Social mega category: social impacts + values + temporal + spatial imbalances + education + stakeholders; Techno-economic mega category: technology + economy.
4. Appropriateness for Sustainability Knowledge Assessments

Cmaps overcome many of the disadvantages of traditional assessments, while being especially appropriate for capturing sustainability knowledge. First, cmaps are open-ended assessments that do not restrict or bias student responses, which is ideal for capturing student knowledge about the broad, ever-changing, and subjective domain of sustainability\textsuperscript{41-44}. Second, cmaps allow students to not only share the concepts they associate with sustainability, but also the relationships between those concepts. As a result, concept-map-based assessments are ideal for capturing how well students grasp the inherent interrelationships between sustainability dimensions\textsuperscript{15}. Third, the ability of cmaps to capture both content and structure makes them useful for identifying whether sustainability knowledge is absent, incomplete, or incorrect, and subsequently identify whether interventions should promote knowledge addition, enrichment, or change, respectively\textsuperscript{26, 27}. Fourth, cmaps are often simpler to create than essays, presentations, or posters\textsuperscript{30}, which allows students to focus on their understanding of the material, rather than on development of the construct. Overall, cmaps provide an innovative way for educators to examine the sustainability knowledge of their students.

5. Previous Studies using Cmaps for Sustainability Knowledge Assessments

Due to their appropriateness, some educators are beginning to use cmaps to measure student sustainability knowledge. For instance, effectiveness of ten sustainability courses in the United Kingdom (UK) was investigated by comparing categorical scores for 506 student cmaps\textsuperscript{24, 25}. Borrego et al.\textsuperscript{23} used cmaps and the holistic scoring approach to analyze the outcomes of a green engineering course. Cmaps were also used to examine the sustainability knowledge of middle school geography students in the UK, which revealed the tendency of students to over-emphasize the environmental dimension\textsuperscript{22}. Use of cmaps as assessment tools has also been suggested for characterizing student understanding of social sustainability in a sustainable construction course, although no corresponding data was reported\textsuperscript{45}. The usefulness of cmaps for examining sustainability knowledge is beginning to be realized, although only a limited number of reports are available.

Methods

A variety of methods were used to gather, score, and analyze student concept maps. Specifically, a mixed methods approach, characterized by collection and analysis of both quantitative and qualitative data in a single investigation, was employed. Qualitative cmap data was transformed into a set of quantitative metrics in a process coined “quantitizing\textsuperscript{46},” which may be considered a mixed-method\textsuperscript{47}.
Gathering Student Concept Maps

The content and structure of student sustainability knowledge was measured at the beginning of capstone design courses using student-generated cmaps. After participating in a 45 minute concept mapping workshop where students learned how to construct cmaps using CmapTools®, a free concept mapping software, they created cmaps on the focus question: “What is sustainability?” While students were not allowed to use outside materials, they were provided with handouts on how to construct cmaps, adapted from several authors, and on how to use CmapTools®.

Scoring Concept Maps

All submitted cmaps ($n = 144$) were analyzed by two expert judges. The traditional and holistic (Table 1) approaches were used to capture the breadth, depth, and connectedness of student knowledge. The categorical method was used to provide data on the topics that students most associated with sustainability, as well as the overall complexity of cmaps (Table 3). To improve inter-rater reliability, judges calibrated scoring procedures by individually scoring multiple cmaps and then discussing differences. Afterward, judges individually scored remaining cmaps, and any discrepancies were discussed to reach a set of consensus scores, as per Borrego et al. Consensus scores were used for all subsequent statistical analysis, including the use of one-way analysis of variance (ANOVA) to detect differences in cmap scores by major. Statistical computations were completed using IBM’s Statistical Package for the Social Sciences (SPSS) (Version 20).

Inter-rater Reliability of Concept Map Scores

Judges’ individual scores were used to quantify inter-reliability based on Krippendorff’s alpha, which is appropriate for any number of judges and any type of data (Table 4). While Cohen’s kappa is the more commonly-used metric for inter-rater reliability, it is intended for use with two judges generating nominal data. The traditional, most objective, method yielded the highest inter-rate reliability statistics, with Krippendorff’s alpha within the adequately acceptable range ($\alpha \geq 0.80$). The categorical method, which requires somewhat subjective assignment of concepts according to a ten-category taxonomy, also exhibited Krippendorff’s alpha within the adequately acceptable range ($\alpha \geq 0.80$). The holistic approach, which relies on judges to apply a rubric in scoring cmaps, showed the lowest inter-rater reliability statistics, although Krippendorff’s alpha were within the acceptable for exploratory research ranges ($\alpha \geq 0.67$). Thus, the traditional, holistic, and categorical scores presented for student sustainability cmaps are reliable.
Table 4. Inter-rater reliability and internal consistency of traditional, holistic, and categorical concept map scoring methods (n = 138, unless otherwise noted).

<table>
<thead>
<tr>
<th>Method</th>
<th>Krippendorf’s Alpha\textsuperscript{a}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional Method</td>
<td></td>
</tr>
<tr>
<td>Number of concepts</td>
<td>1.000</td>
</tr>
<tr>
<td>Highest level of hierarchy</td>
<td>0.959</td>
</tr>
<tr>
<td>Number of cross-links</td>
<td>0.984</td>
</tr>
<tr>
<td>Holistic Method</td>
<td></td>
</tr>
<tr>
<td>Comprehensiveness</td>
<td>0.761</td>
</tr>
<tr>
<td>Organization</td>
<td>0.758</td>
</tr>
<tr>
<td>Correctness</td>
<td>0.774</td>
</tr>
<tr>
<td>Categorical Method</td>
<td></td>
</tr>
<tr>
<td>Concept assignment (n = 1806)</td>
<td>0.859</td>
</tr>
<tr>
<td>Number of interlinks</td>
<td>0.830</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Krippendorf’s alpha for ratio data used for NC, NH, HH, NCL, and NIL. Krippendorf’s alpha for interval data used for comprehensiveness, organization, and correctness. Krippendorf’s alpha for nominal data used for concept assignment.

Results

Traditional Scoring Method

The structure and content of student-generated sustainability cmaps were analyzed using the traditional scoring method. The mean number of concepts, which indicates knowledge breadth, was 13.4, while the highest hierarchy, which captures knowledge depth, was 3.4. The number of cross-links, a measure of the connectedness of student knowledge, was only 2.4. The mean total cmap score was computed to be 51.6. Disaggregating the data by major revealed no statistically significant differences.

Table 5. Mean traditional scores for sustainability cmaps created by capstone design students

<table>
<thead>
<tr>
<th></th>
<th>Mean Traditional Cmap Scores</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CE (n = 113)</td>
<td>EnvE (n = 31)</td>
</tr>
<tr>
<td>Number of Concepts</td>
<td>13.3</td>
<td>13.7</td>
</tr>
<tr>
<td>Highest Hierarchy</td>
<td>3.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Number of Cross-Links</td>
<td>2.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Total</td>
<td>51.3</td>
<td>53.0</td>
</tr>
</tbody>
</table>
Holistic Scoring Method

In addition to the traditional method, the holistic approach was used to examine the content and structure of student sustainability knowledge displayed in cmaps. The mean comprehensiveness sub-score, which reflects the breadth and depth of knowledge, and the mean organization sub-score, which rates the connectivity and placement of concepts, were each only 1.3 on a three-point scale. However, the mean correctness score was 2.9 on three-point scale, which suggests that student knowledge was mostly valid and contained few misconceptions. The mean total (holistic) cmap score (Table 1) was 5.4 out of a maximum of 9.0 points. No significant differences in holistic scores were found based on academic major.

<table>
<thead>
<tr>
<th></th>
<th>CE (n = 113)</th>
<th>EnvE (n = 31)</th>
<th>Combined (n = 144)</th>
<th>F(1, 142)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comprehensiveness</td>
<td>1.3</td>
<td>1.4</td>
<td>1.3</td>
<td>0.521</td>
<td>0.472</td>
</tr>
<tr>
<td>Organization</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>0.195</td>
<td>0.660</td>
</tr>
<tr>
<td>Correctness</td>
<td>2.9</td>
<td>2.9</td>
<td>2.9</td>
<td>0.519</td>
<td>0.472</td>
</tr>
<tr>
<td>Total</td>
<td>5.4</td>
<td>5.6</td>
<td>5.4</td>
<td>1.053</td>
<td>0.307</td>
</tr>
</tbody>
</table>

Categorical Scoring Method

The categorical scoring method was used to supplement the analysis provided by the traditional and holistic approaches. Category relevancies show natural resources (28.9%) and the environment (23.5%) to be the categories most included in student cmaps, with spatial imbalances (0.12%) and education (0.97%) being the least included categories. In addition, cmaps constructed by CEE students included an average of 6.6 inter-links, or connections between concepts from different categories. The mean student-level complexity index (CO\textsubscript{j}), which indicates the overall quality of sustainability knowledge, was computed to be 10.8. Using metrics defined by Segalàs et al.\textsuperscript{25} (Table 3), the cohort-level complexity index (CO\textsubscript{cohort}) was 8.8. No statistical differences were identified between civil and environmental engineering students.
Figure 2. Category relevancies (CR$_i$) for sustainability cmaps created by capstone design students ($n = 144$) (Other represents stakeholder, values, education, and spatial imbalances).

Table 7. Mean categorical scores for sustainability cmaps created by capstone design students.

<table>
<thead>
<tr>
<th></th>
<th>Mean Categorical Cmap Scores</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CE ($n = 113$)</td>
<td>EnvE ($n = 31$)</td>
</tr>
<tr>
<td>Number of Inter-Links</td>
<td>6.4</td>
<td>7.3</td>
</tr>
<tr>
<td>Complexity Index $^a$ (CO$_{cohort}$)</td>
<td>10.0</td>
<td>12.0</td>
</tr>
</tbody>
</table>

$^a$Cohort-level complexity index (CO$_{cohort}$), as defined by Segalas $^{25}$ (Table 3), calculated as 8.8 for CEE students.

**Discussion**

**Analyzing Student Sustainability Knowledge based on Concept Map Scores**

Cmap scores suggest overall student sustainability knowledge to be somewhat limited. In fact, the mean total holistic score for student-generated cmaps was only 5.4 out of 9.0. In addition, the mean complexity index (CO$_{cohort}$, categorical method) for CEE students was 8.8, as compared to 24.8 for a group of 19 sustainability experts$^{41,52}$. Similarly, Azapagic et al.$^{53}$ documented the sustainability knowledge of chemical engineering students world-wide to be “not satisfactory,” while only approximately 35% of University of Plymouth students were “very familiar” with sustainable development Kagawa$^{54}$. Other authors have also documented deficiencies in student sustainability knowledge$^{55-58}$. Like other students internationally, CEE students demonstrated limited sustainability knowledge, which suggests potential for future knowledge enrichment.
Cmap scores also support the need to improve the depth and breadth of student knowledge. The holistic approach shows that the mean comprehensiveness sub-score, which encompasses both breadth and depth of student knowledge, was especially low (1.3 on a three-point scale). Similarly, the mean number of concepts (an indicator of knowledge breadth) was only 13.4 for CEE undergraduates, as compared to 19.8 for sustainability experts and 16.9 for UK students having completed a variety of sustainability-related courses.

Student-generated cmaps show that students have an unbalanced perspective of sustainability. For instance, category relevancies suggest that student cmaps over-emphasize environmental concepts ($CR_{\text{environmental}} = 50.7\%$), as compared to economic ($CR_{\text{economic}} = 25.5\%$) and social concepts ($CR_{\text{social}} = 23.7\%$). While promoting sustainability inherently requires an understanding and balancing of sustainability dimensions, many authors have suggested that some university stakeholders, from undergraduates to facilities managers, over-emphasize the environmental aspects of sustainability. A similar trend was also observed for middle school geography students in the UK. As a result, educators should strive not only to enrich the depth and breadth of student knowledge, but to ensure that students acquire a balanced perspective of sustainability.

Results support that improvement in the connectedness of student knowledge networks are needed. Cmaps only included an average of 2.4 cross-links and 6.6 inter-links. In addition, the mean organization sub-score (holistic method) was only 1.3 out of 3.0. For comparison, CEE graduate students included an average of 4.6 and 10.6 cross-links and inter-links, respectively, while sustainability experts included an average of 19.8 inter-links. Since connectedness of knowledge increases one’s ability to access concepts and is a key feature that differentiates expert and novice knowledge frameworks, additional work is needed to aid CEE students in making connections between sustainability dimensions.

Comparing Assessments for Civil and Environmental Engineering Students

Sustainability knowledge was indistinguishable between civil and environmental engineers. Specifically, no statistical differences were found between total cmap scores or any of the individual sub-scores. In addition, both civil and environmental engineers alike were found to over-emphasize environmental sustainability. In contrast to this study, Bielefeldt found environmental engineering students to be more confident in their knowledge of the term sustainability than civil engineering students. Bielefeldt also reported that more environmental engineering students (86%) than civil engineering students (74%) were able to select the three sustainability pillars in a multiple-choice question. Perhaps no difference in sustainability knowledge by major was found in the current study because open-ended construction of cmaps is more difficult than answering one closed-ended question.
Concept-map-based assessments provide several insights for improving sustainability education in CEE at Georgia Tech. Foremost, all three scoring approaches support that there is potential to improve student sustainability knowledge. Second, although student knowledge is limited, the mean correctness sub-score of 2.9 on a three-point scale suggests that student knowledge is not plagued with inaccuracies. As a result, interventions are needed to simply enrich student knowledge, which is considerably easier than correcting misconceptions. Finally, cmaps, when scored using the categorical approach, clearly reveal specific qualities of student sustainability knowledge that need to be enriched. Thus, student knowledge assessments suggest the need for, type of, and necessary outcomes of interventions to improve student understanding of sustainability.

Broad Implications for Selecting Sustainability Knowledge Assessments

Results of this study can broadly be applied to aid in selection and administration of sustainability knowledge assessments within many academic programs and institutions. The literature shows that student surveys are one of the predominant methods for analyzing student sustainability knowledge. While insights gained from such perceptions surveys can undoubtedly help guide curricular reforms, research has shown that students often over-state their cognitive abilities when asked to rate their own knowledge. Use of cmaps as direct measures of student knowledge, as demonstrated in the current study, can serve as a more accurate assessment tool than self-report surveys. While other authors have cautioned against the use of cmaps due to scoring difficulties, the current study outlines three reliable scoring techniques that can be feasibly applied to a large sample of cmaps. Thus, cmaps may be used to more effectively characterize sustainability knowledge to guide and assess education reform efforts.

Conclusions

An investigation was conducted to demonstrate the use of cmaps for evaluating student sustainability knowledge. Seniors enrolled in CEE capstone design courses at Georgia Tech constructed cmaps to depict their sustainability knowledge, and judges were employed to score the cmaps using traditional, holistic, and categorical approaches. The following conclusions were made based on the results.

1. CEE students’ overall sustainability knowledge is limited and displays little interconnectedness, which is an indicator of novice understanding.
2. Students have an unbalanced perspective of sustainability that favors the environmental dimension.
3. Educational interventions are needed to enrich student understanding and create sustainability knowledge networks that are balanced (in breadth and depth) and interconnected.

4. While student surveys are the dominant tool for assessing sustainability knowledge, more objective tools, such as cmaps, can be employed to provide a holistic and detailed assessment of student understanding.

As the global landscape continues to evolve, engineers will be required to adapt their skills and professional practices to meet the needs of present and future generations. Already, engineers are increasingly called upon to develop and implement innovative solutions that serve a growing population, while simultaneously exploiting fewer resources and minimizing environmental impacts. As a result, it is imperative that engineering educators strive to equip their students with the knowledge necessary to act as sustainability-conscious engineers. Accurate sustainability knowledge assessments can aid in this endeavor by informing the design and evaluating the effectiveness of efforts to infuse sustainability content into undergraduate courses and curricula.

References

9. MacRae, J.D. Introducing elements of sustainability into formal and informal environmental engineering education. in American Society for Engineering Education (ASEE) Annual Conference & Exposition. 2011. Vancouver, BC.
40. Watson, M.K., Dissertation: Assessment and Improvement of Sustainability Education in Civil and Environmental Engineering, in Civil and Environmental Engineering. 2013, Georgia Institute of Technology: Atlanta, GA.


