Exploring Student Sustainability Knowledge using the Structure of Observed Learning Outcomes (SOLO) Taxonomy

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Introduction

Sustainable Development: The Concept

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 by the United Nations (UN) World Commission on Environment and Development (UNWCED) 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[1]" (also called Brundtland definition). The Johannesburg Declaration, released after the UN World Summit on Sustainable Development (UNWSSD), later proposed the three pillars of sustainable development to be economic development, social development, and environmental protection[2]. While endorsing sustainability requires valuing all three dimensions (i.e. economy, environment, and society)[3, 4], it has been suggested that the environmental dimension is often over-emphasized[5-8], while the less-developed social dimension is underemphasized[9]. Some authors have suggested that additional dimensions be added to the three-pillars conceptual framework, including temporal[4] and institutional dimensions[10]. Nevertheless, the dimensions of sustainability are complex and interrelated, and promoting sustainable development requires that tradeoffs between dimensions be simultaneously balanced.

Sustainable Development: The Reality

While the concept of sustainability seems abstract, there have been global efforts to embrace the sustainable development paradigm. For instance, the Peabody Trust and BioRegional Development Group partnered to create the Beddington Zero-Energy Development (BedZED) in the London Borough of Sutton (completed in 2002). The ultimate goal of this project was to "enable people to live sustainably without sacrificing a modern, urban and mobile lifestyle[11]." To ensure that their project was indeed sustainable, the designers of this innovative community set and accomplished a variety of environmental, social, and economic goals. Environmentally, the development produces no net carbon dioxide emissions, utilizes alternative energy (such as solar via photovoltaics), and strives to protect biodiversity. Socially, the community includes two-thirds affordable housing and a healthy living center. Economically, BedZED exploits local forms of renewable energy sources and other building materials, as well as provides space for local businesses[11].

The outcomes of this sustainable community are impressive. For instance, monitoring of the development shows 45% reduction in electricity use (compared to the local average), 58% reduction in water use (compared to local average), 64% reduction in car mileage (compared to national average), and 60% of community waste being recycled, among other statistics[12]. Overall, residents of BedZED that adopt all of the "green lifestyle features" can reduce their ecological footprint from 3 to 1.9 planets[13]. A report published seven years after completion of BedZED heralds the project as a "success," despite some disappointments related to the biomass combined heat and power (CHP) plant[13]. Overall, the BedZED project was among the first developments to truly showcase an environmentally, socially, and economically-sustainable community.

Sustainability and Engineering Education

As the designers of infrastructure that will have lasting impacts on the economy, environment, and society, engineers are particularly poised to significantly advance sustainable development[14]. In fact, sustainable engineering has emerged as a new field aimed at integrating and balancing economic, environmental, and social systems during development[3]. While there may be a new breed of sustainable engineers, there is a need for practitioners from all engineering disciplines to promote sustainability through sustainable design[15].

As a result, many organizations have endorsed the training of sustainability-conscious engineers. 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[16]." 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[17]". In 1996, the American Society of Civil Engineers revised its Code of Ethics to include sustainability principles as part of the canon of civil engineering practices[18]. Due to the impact that engineers can have on promoting sustainable development, it is not only critical, but also mandatory, that undergraduate education train engineers to understand and apply sustainability principles during design.

Despite the importance of sustainable design, undergraduate curricula may not properly equip students with the knowledge and skills to engage in this practice. Specifically, curricula in higher education have been criticized as emphasizing disciplinary specialization and reductionist thinking[19-21]. 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[21]. In contrast, the complex nature of global and local dilemmas necessitates that scientists exercise interdisciplinary and systems thinking to understand and balance the interrelated technical, economic, environmental, and social dimensions of a problem[22]. Thus, significant changes are needed to integrate sustainability content into undergraduate engineering curricula to properly educate students to tackle complex global dilemmas[23-26].

Key to the development and monitoring of these reform efforts will be the availability of accurate and reliable tools for assessing student sustainability knowledge. Most commonly in the literature, student sustainability knowledge is characterized using indirect student perceptions surveys[27]. While such tools can provide a rough picture of student knowledge, direct assessments often provide a more complete picture of student understanding[28]. Two types of direct assessments presented in the literature for capturing sustainability knowledge are concept maps (cmaps)[29, 30] and Structure of Observed Learning Outcomes (SOLO)-based assessments[14, 31, 32]. While the content and structure of student knowledge are accurately captured in cmaps, scoring of these constructs can become tedious if the student sample is large or if student knowledge is extremely complex[33]. Application of the SOLO taxonomy, a discipline-independent schema of conceptual development[34], to analyze student sustainability knowledge has also been presented to a limited extent in the literature[31] and may prove to be a more feasible direct assessment than cmaps.

Project Overview

The goal of this project is to explore application of the SOLO taxonomy as a relatively quick assessment of student sustainability knowledge. Specifically, a case study examining the sustainability knowledge of senior civil and environmental engineering (CEE) students at the Georgia Institute of Technology (Georgia Tech) was analyzed through the lens of the SOLO taxonomy. The following research questions were addressed: (1) How structurally advanced is student sustainability knowledge? (2) Which sustainability dimensions do students most associate with sustainability? and (3) How appropriate is application of the SOLO taxonomy for sustainability knowledge assessments?

Background Information: Sustainability Knowledge Assessments

With increasing interest in incorporating sustainability into engineering curricula, there have been a variety of assessment tools presented in the literature to help guide and evaluate these reform efforts. Although indirect student surveys are most commonly presented, concept maps (cmaps) and the SOLO taxonomy are emerging tools that may provide a more direct and accurate snapshot of student sustainability knowledge.

Student Surveys

Student perceptions surveys are perhaps the most commonly used tools for examining sustainability knowledge. Emanuel and Adams[35] surveyed 554 undergraduates from institutions in Alabama and Hawaii and reported that only approximately one-third of respondents indicated that they knew "a great deal" about sustainability. Azapagic et al.[36] documented the sustainability knowledge of chemical engineering students world-wide to be "not satisfactory," while only approximately 35% of University of Plymouth students in the United Kingdom were "very familiar" with sustainable development[37]. Even still, first-year civil engineering students at the University of Colorado were most commonly "slightly familiar" with the term sustainability, as compared to first-year environmental engineering students that were most frequently "somewhat familiar[38]". Examination of over 1000 students at Leuphana University of Lüneburg in Germany showed undergraduates to possess a "sophisticated" understanding of sustainability, although students placed great emphasis on the environmental dimension[39]. Overall, surveys from a variety of countries and institutions suggest deficiencies in the sustainability knowledge of undergraduates and an over-emphasis of environmental sustainability. While insights gained from such perceptions surveys can undoubtedly help guide curricular reforms[40], research has shown that students often over-state their cognitive abilities when asked to rate their own knowledge[41-43]. Consequently, measures to improve student knowledge and skills may need to be more aggressive than suggested by indirect surveys.

Concept Maps

Cmaps can provide a more direct measure of student sustainability knowledge than perceptions surveys[33]. Briefly, cmaps are graphical tools for organizing knowledge that allow students to depict their understanding of a domain by arranging related concepts and using directive, descriptive linking lines to show relationships between those concepts[44, 45]. Constructing cmaps allows students to freely reveal both the content and structure of their understanding. As a result, concept-map-based assessment tools are ideal for characterizing broad student conceptions about sustainability, as well as capturing how well they grasp the inherent interrelationships between sustainability dimensions. Although cmaps are extremely promising as sustainability knowledge assessments, practical methods for scoring cmaps are needed before concept-map-based assessment tools are widely applied[28, 46-48].

A few authors have used cmaps to characterize student sustainability understanding. Segalàs et al.[49] investigated the effectiveness of ten sustainability courses by comparing 506 student cmaps before and after delivery of several sustainability-related courses. Borrego et al.[29] analyzed cmaps before and after a green engineering course using a holistic scoring rubric and found that the comprehensiveness, correctness, and organization of student maps increased after course delivery. In addition, Watson[33] used cmaps to demonstrate changes in student knowledge before and after a sustainability module using three different cmap scoring methods. 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[50-52]. Thus, cmaps are beginning to be applied as assessment tools for studying student sustainability knowledge, but additional work is needed to evaluate scoring methods[28, 33, 46-48].

SOLO Taxonomy

In addition to cmaps, application of the SOLO taxonomy is another direct measure of sustainability knowledge presented in the literature. Based on Piaget's stages of cognitive development, Biggs and Collis[34] first presented the SOLO taxonomy for capturing adult conceptual development (Table 1). Students are described as passing through five sequential stages in their pursuit of understanding in any discipline[34, 53]. Beginning in the *pre-structural* phase, students have virtually no knowledge of the subject. The *uni-structural* and *multi-structural* stages consist of students acquiring fundamental content knowledge. Afterward, students move beyond content knowledge and begin to develop structural complexity as they see relationships between concepts in the *relational* phase. Finally, students acquire the ability to generalize concepts beyond the context in which they were learned in the *extended abstract* phase[31, 34].

At its foundation, the SOLO taxonomy is a stage theory for describing conceptual development[31, 34]. Defined strictly, stage theory suggests that students develop conceptual knowledge by progressing linearly through hierarchical stages of understanding. While Carew and Mitchell[31] protest that it is unlikely for *all* students to develop in the same manner, they support the value of stage theory for describing the variations in knowledge that may exist for a group of students. In fact, they support that understanding differences in student knowledge can facilitate development of teaching and learning strategies, as well as assessment procedures[31]. Indeed, the SOLO taxonomy has been applied in several disciplinary contexts to examine the wide variety of conceptual and structural development that exists among students even with similar educational backgrounds[14, 31, 32, 54, 55]. In addition, the SOLO taxonomy has been used as an assessment tool to monitor the effect of educational interventions using pre- post-test experimental designs[32, 56].

Specifically, the SOLO taxonomy has been used to a limited extent to examine student conceptions about sustainability. In a survey administered to 52 chemical engineering students in Australia having previously completed a sustainability course, Carew and Mitchell[31] collected student responses to the question: "In your own words, what is sustainability." With 78% rater agreement, over half (55.8%) of student definitions were characteristic of the *uni-structural* category. In a similar study, Hayles[32] prompted students to answer the question "What is your definition of sustainability?" before and after a sustainability-focused construction management course in Australia. Classifying responses according to the SOLO taxonomy showed a shift between *pre/uni-structural* definitions at the beginning of the course to *uni/multi-structural* definitions at the end of the course. Finally, Nicolaou and Conlon[14] surveyed 143 engineering and building services students from three different Irish higher education institutions and asked them to provide definitions of sustainability. Most responses were classified as *uni-structural* (57.3%) or *mult-structural* (31.8%). A content analysis of the definitions also showed that students most associated sustainability with environmental or economic topics, rather than social ones. While a few authors have used the SOLO taxonomy to examine variations in student sustainability knowledge, no study has yet presented rigorous inter-rater reliability statistics (beyond simple percent agreement) and content analysis of topics presented in student definitions, along with the SOLO stage classifications.

Research Methods

A variety of data collection and analysis methods were used to demonstrate the use of the SOLO taxonomy as a feasible tool for analyzing student sustainability knowledge.

Student Sample

Students enrolled in a CEE capstone design course at Georgia Tech were recruited to participate in this study (n = 63). Most participants were male (84.1%) civil engineering students (82.5%) from the United States (77.4%). Student recruitment and engagement practices were approved by the Institutional Review Board (IRB) at Georgia Tech.

Table 1. Structure of Observed Learning Outcomes (SOLO) taxonomy for classification of non-disciplinary[34] and sustainability-related[31] conceptual development.

SOLO Stage	Overview of SOLO Stage[34]	Features of Sustainability Definition Typical of Each Stage[31]
Pre-Structural	Student demonstrates no understanding of the desired learning.	Either did not know what sustainability was or provided a broad, non-specific response.
Uni-Structural	Student demonstrates understanding of only one item relevant to the desired learning.	Provided one definitive example of something concrete or abstract with relevance to sustainability.
Multi-Structural	Student demonstrates understanding of more than one relevant item, but items are seen as independent or unrelated to each other.	Provided two or more qualitatively different examples of concrete and/or abstract things relevant to sustainability.
Relational	Items are described as part of an overall structure and as being interrelated (not necessarily a greater number of items nominated than in multi-structural).	Constructed a cohesive, internally consistent statement about sustainability by relating two or more concrete and/or abstract things relevant to sustainability.
Extended Abstract	Items are described as part of an overall structure, and elements of the structure are seen to be applicable in other situations (i.e. transferable or generalizable).	Constructed a cohesive, internally consistent statement about sustainability by relating two or more concrete and/or abstract things related to sustainability, and provided evidence of critical thinking, ethical judgment, consideration of context or creative/original thinking relevant to sustainability.

Data Collection

Participants were directed to complete an extended Student Sustainability Survey during their capstone design course. Specifically, students responded to an open-ended prompt asking them to "in [their] own words, define sustainability," as was suggested by previous authors[14, 31]. Although students were asked to respond to a variety of other questions related to their sustainability knowledge[40], those responses were not used as part of the current study. Students were given the duration of the three-hour class to complete the survey, but no student took longer than 45 minutes. Student definitions were transcribed and assigned alphabetic identification codes to protect student identity.

Data Analysis

Student sustainability definitions were analyzed by expert judges. Before judges proceeded with official scoring, they engaged in training and calibration sessions.

1. Expert Judges

Two judges analyzed student sustainability definitions. The first judge was a PhD student in CEE, while the second judge held an advanced degree in Electrical and Computer Engineering. Both judges completed sustainability-related courses, conducted sustainability-related research, and have been involved with Engineers without Borders (EWB), an organization dedicated to implementing sustainable engineering projects worldwide. Both judges extensively reviewed recent publications related to sustainability and sustainability education prior to scoring student definitions.

2. Judge Training and Calibration

Judges were trained to apply the SOLO taxonomy before rating sustainability definitions collected in the CEE capstone design course. Judges reviewed previous publications[31, 32] outlining the use of the SOLO taxonomy for sustainability knowledge assessments. Afterward, judges individually scored ten sustainability definitions composed by CEE sophomores. Judges classified the statements according to the sustainability-specific SOLO taxonomy (Table 1). They also classified sustainability topics/concepts present in definitions according to a ten-category system proposed by Segalas et al.[30] (Table 2). Judges compared scores and discussed discrepancies to standardize future scoring, as was practiced by previous authors[31]. This calibration procedure was completed with ten additional sustainability definitions to further improve inter-rater reliability.

Table 2. Examples of concept categorization based on ten sustainability categories [Adapted from Coral[57] and Segalàs et al.[30]].

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

3. Analysis of Student Sustainability Definitions

After practice sessions, judges systematically scored sustainability definitions composed by senior CEE students. For each student submission, each judge assigned the definition to an appropriate SOLO class (Table 1). In addition, each judge classified key sustainability topics presented in definitions according to an *a priori* set of ten sustainability categories[30] (Table 2). Judges' individual scores were used to quantify inter-rater reliability using Krippendorff's alpha, which is a statistic that is appropriate for any number of judges and any type of data[58]. Scores with Krippendorff's alpha above 0.80 were designated as adequately acceptable, while values above 0.67 were classified as acceptable for exploratory research[58, 59]. Discrepancies were discussed among judges, and consensus scores were used for subsequent statistical analyses, as suggested by other authors[28, 31].

Results

A study was completed at Georgia Tech to demonstrate application of the SOLO taxonomy for examining complexity of student sustainability knowledge. Student-composed sustainability definitions were examined by expert judges to determine the appropriate SOLO stage and identify relevant sustainability topics addressed. Inter-rater reliability of judges' scores was also quantified.

Structural Complexity based on SOLO Taxonomy

Of the five SOLO stages, a majority (55.6%) of CEE seniors demonstrated a *multi-structural* understanding of sustainability (Figure 1). Consequently, judges observed that most students demonstrated knowledge of multiple relevant sustainability concepts, but failed to describe relationships between the concepts. For instance, many students (Table 3) referenced both environmental and temporal considerations. However, some (6.3%) students did achieve *relational* understanding, as evidenced by their descriptions of the inherent interrelationships between sustainability pillars (economy, environment, and society), as well as temporal aspects (Table 3). Over one-third of students showed *pre-structural* (4.8%) or *uni-structural* (33.3%) understanding. *Pre-structural* definitions were vague or biased, while *uni-structural* definitions mentioned only one sustainability dimension (Table 3).

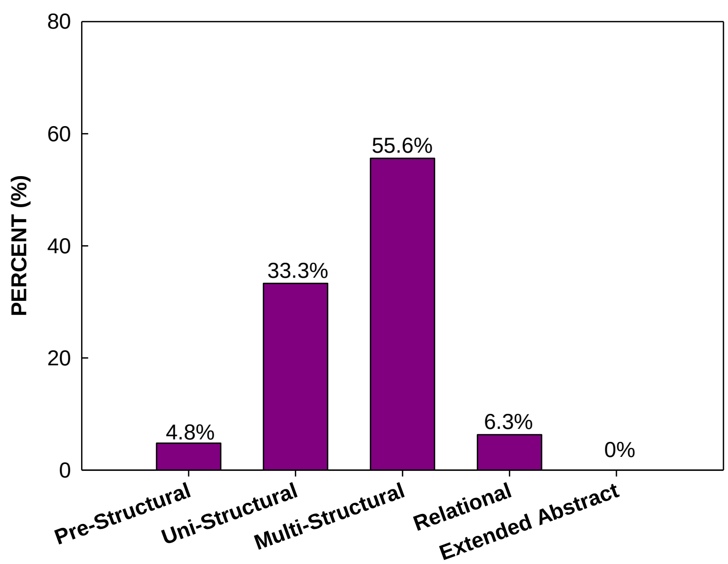

Figure 1. Variations in CEE seniors' sustainability knowledge (n = 63).

Table 3. Examples of student sustainability definitions and judges' consensus classifications according to the SOLO taxonomy.

SOLO Stage	Student Example 1	Student Example 2
Pre-structural	"An expensive way to make buildings, roads, etc. that don't hurt habitats of deer and squirrels."	"Sustainability is a system that works in such a manner that does not impact or affect others and works efficiently."
Uni-Structural	"Sustainability is the attempt to reduce the negative impact a project can have on the existing environment."	"Sustainability to me is the ability for us to build without restricting future generations from doing so as well."
Multi-Structural	"Sustainability is the concept of using materials and energy in a way that will not affect the population of the future."	"Providing for the needs of the present while maintaining the environment and resources for the needs of the future."
Relational	"Responsible planning and use of natural and economic resources with long-term survival and advancement of humans and the planet in mind."	"The use of resources in a way that enhances the current situation economically, environmentally, and socially without causing the hindrance of future generations to do the same."
Extended Abstract	N/A	N/A

Sustainability Content Knowledge

Among the sustainability topics and concepts discussed in student definitions, most were related to the social or environmental dimensions (Figure 2). Within the social sector, over one-third of concepts discussed by students underscored the importance of protecting future generations ("temporal" category" from Table 2). Also commonly included in definitions were considerations of societal impacts, especially those related to human health and well-being. In addition, concerns for the environment and natural resources accounted for over 40% of all topics included in sustainability definitions. Economic and technical considerations related to sustainability were largely omitted from student definitions.

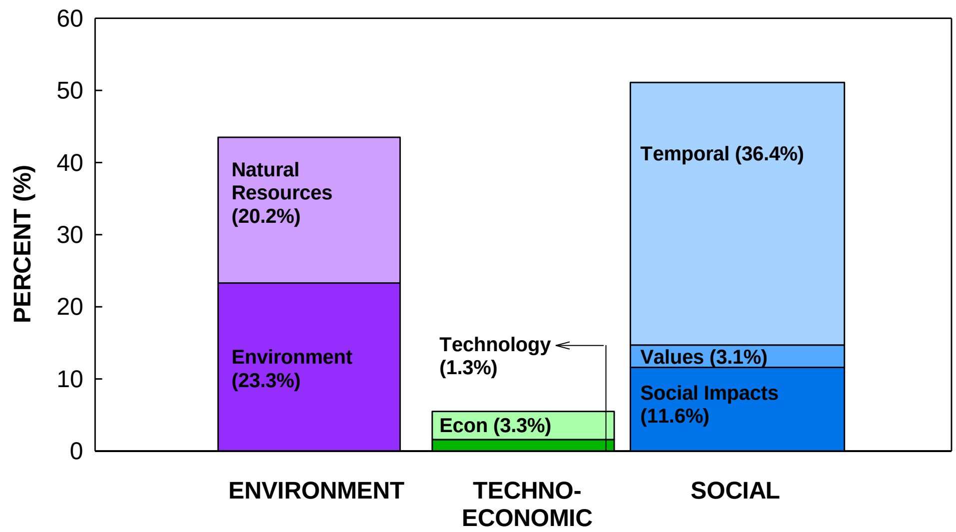

Figure 2. Content of CEE seniors' sustainability knowledge.

Interrater Reliability

Based on Krippendorff's alpha, judges' scores were sufficiently in agreement. In fact, Krippendorff's alpha for classification of definitions according to SOLO stages (Table 1, Figure 1) was 0.68. For assignment of sustainability topics appearing in definitions to the ten sustainability categories (Table 2, Figure 2) was 0.69. Both statistics were above 0.67, which deems the data "appropriate for exploratory research[58, 59]."

Discussion

The results of this study were synthesized to address the three primary research objectives previously outlined. Specifically, results provide insights into the sophistication and comprehensiveness of student knowledge, as well as broad implications for sustainability knowledge assessments.

How structurally advanced is student sustainability knowledge?

Analyzing student definitions using the SOLO taxonomy revealed that most students had a *uni-structural* or *multi-structural* understanding of sustainability. Consequently, students were able to list one or more examples of sustainability topics, but they were unable to weave concepts together to produce a cohesive sustainability definition. Demonstration of *multi-structural* sustainability knowledge, which was characteristic of over half of student definitions, is reasonable, since seniors had previously completed Civil Engineering Systems[40, 60], a sustainability-focused course. In addition, the CEE faculty at Georgia Tech have previously indicated that they also incorporate sustainability topics into traditional engineering courses (horizontal integration)[40].

It is possible that participants in the current study were more knowledgeable about sustainability than those in previously-published studies. For instance, both Carew and Mitchell[31] and Nicolaou and Conlon[14] reported that over half of their participants demonstrated *uni-structural* sustainability knowledge, while *multi-structural* understanding predominated in the current study. Like CEE seniors, Carew and Mitchell's[31] chemical engineering students had completed a sustainability- focused course. Perhaps the CEE course was more comprehensive or CEE faculty efforts to weave sustainability across the curriculum were effective. Scores reported by Nicolaou and Conlon[14] were for a wide range of engineering majors, which may suggest variations in curricular content and sustainability knowledge across disciplines. On the other hand, as is expected in qualitative research, it is feasible that discrepancies in scores among these three studies result due to differences in judges' interpretations of student definitions[31]. Consequently, the results are "justifiable[31]" but not "reproducible[31]."

Which sustainability dimensions do students most associate with sustainability?

The predominant topics included in student sustainability definitions were environment/natural resources and intergenerational equity (temporal considerations). It is not surprising that students heavily emphasized environmental concepts, given that students from a variety of backgrounds have been shown to favor environmental sustainability[14, 30, 37, 39, 61-63]. In addition, CEE seniors at Georgia Tech also indicated in a survey that they were most interested in environmental sustainability, as compared to social or economic sustainability[40]. Emphasis on temporal aspects of sustainability may have been evident due to student reliance on the Brundtland definition[1], which is arguably the most famous definition of sustainability. Furthermore, CEE students rarely mentioned the social impacts of sustainability, which corresponds to previous authors which have demonstrated that social sustainability is often neglected[9, 52].

How appropriate is application of the SOLO taxonomy for sustainability knowledge assessments?

Overall, the SOLO taxonomy is a relatively quick and reliable method for analyzing student sustainability knowledge. Foremost, this study demonstrated that rigorous training of judges can help to ensure acceptable inter-rater reliability of SOLO classifications. Second, SOLO classifications indicated that additional educational interventions may be useful in helping students move beyond *uni-structural* and *multi-structural* understanding to see important relationships between sustainability concepts. Although the SOLO taxonomy is useful for identifying variations in student knowledge, it does not reveal the specific concepts and topics that students associate with sustainability. However, as was completed in this study and by others[14], an *a priori* coding scheme can be used to further analyze student definitions. Using such a scheme allows the instructor to not only determine whether or not expert knowledge has been achieved, but also identify strengths and weaknesses of student knowledge. As a result, the SOLO taxonomy is a valuable tool for analyzing student sustainability knowledge that can be applied to a wide variety of students, including those from different disciplines and academic standings.

Conclusions

A study was conducted to explore the application of the SOLO taxonomy as a relatively quick assessment of student sustainability knowledge. By applying the taxonomy to student sustainability definitions constructed by a cohort of seniors enrolled in a CEE capstone design course at Georgia Tech, the following conclusions were reached.

1. A majority of students demonstrated a *uni-structural* or *multi-structural* understanding of sustainability, which suggests that additional integration of sustainability into the curriculum may aid students in developing more expert-like knowledge.
2. Students in CEE most captured aspects of environmental sustainability and intergenerational equity in their sustainability definitions, which is similar to other engineering and non-engineering students.
3. The SOLO taxonomy, when used with an *a priori* coding scheme, is useful for directly and reliably capturing not only variations in the level of student knowledge, but also specific strengths and weaknesses of the content of student knowledge.

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. While this is a lofty task, the designers of the BedZED project have demonstrated that it is possible to conceive of and implement a sustainable development project. As a result, it is imperative that engineering educators strive to equip their students with the knowledge necessary to act as sustainability-conscious engineers. Reliable and direct sustainability knowledge assessment tools, such as the SOLO taxonomy, can aid in this endeavor by informing the design and evaluating the effectiveness of efforts to infuse sustainability content into undergraduate courses and curricula.

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