Constructionist Learning for Environmentally Responsible Product Design

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Abstract

Wayne State University, Penn State University, and Oregon State University are developing a distributed cyberlearning environment to facilitate the consideration of different human controlled/initiated impacts on the natural environment through team-based and personalized design activities. This interactive learning environment, Constructionism in Learning: Sustainable Life Cycle Engineering (CooL:SLiCE), supports a constructionist line of inquiry within design practice to enable students to attain a deeper conceptual understanding. This paper focuses on assessing sustainable product design activities and on applying the findings to educational design to support the constructionist learning method. This preliminary study, conducted in classes at multiple participating universities, shows an intermediate analysis about learner engagement, different level of scaffolding, competency, and the depth of conceptual understandings. The eventual goal is to use assessment items developed from this study to test the appropriateness of the CooL:SLiCE framework (e.g., for the effectiveness of constructed knowledge in deep learning, the impacts of different autonomy levels on student learning, and learners’ engagement).

Introduction

Engineering initially was taught as a hands-on discipline. Through the years, however, with advances in science a pedagogical shift to a curriculum delivered via lectures occurred. Such an emphasis limits student learning through experience. Current advances in science, specifically in communication and information technologies, are resulting in a renewed interest in hands-on (physical and virtual) learning. While laboratories in engineering education provide opportunities for hands-on learning, researchers have found that student learning in labs has not achieved the expected benefits \[1, 2\]. There are numerous shortcomings in traditional labs that include, for example, short time constraints and high student expectations \[3\]. When we treat our students as novices receiving existing knowledge (in a lecture and in a highly structured lab), they do not have the opportunity to construct knowledge.

Constructionism, as defined by Papert \[4\], is a pedagogical approach that encourages learning through constructing, or designing or making, a product. Constructionism was inspired by the constructivist learning paradigm \[5, 6\], but it is different. According to constructivism, people construct their own version of reality by extracting abstract and formal knowledge from the learning context. Constructivists contend that learning occurs by collaboratively constructing reality internally. Constructionists, on the other hand, reason that knowledge does not stay inside a learner’s head, but instead binds learning to context and is shaped by the use of external support. Constructionism can help us to understand how “learning is a cyclical process of construction in which the learners externalize their initial state of knowledge through building an object, which helps them update their old knowledge as well as interpret and construct new knowledge” \[7\]. To put it succinctly, under a constructionism paradigm, learning effectively engages learners in designing or constructing something tangible.
Two key learning aspects are inherent to constructionism: scaffolding and autonomy. *Scaffolding* provides structure and guidance through coaching, hints, and task structure, but it does not provide the final answer. Scaffolding changes complex and difficult tasks in ways that make these tasks accessible, manageable, and within student’s zone of proximal development. Fundamental to scaffolding is that it supports students’ learning of both how to do the task as well as why the task should be done that way. *Autonomy* represents an inner endorsement of one’s actions—the sense that one’s actions emanate from oneself and are one’s own. Thus, when students take increased responsibility for their own learning, they are acting autonomously.

In order to provide guidance in critical domain knowledge, we are developing a web-based educational portal in environmentally responsible product design, called Constructionism in Learning: Sustainable Life Cycle Engineering (CooL:SLiCE). This portal allows for student active experiments to build understanding and to test the learned concepts through active experimentation, which fits well within the constructionism approach that underlies the pedagogical philosophy of this study. The project to develop the CooL:SLiCE cyberlearning platform and planned evaluations within this cyber environment are next discussed.

**CooL:SLiCE Cyberlearning Environment**

The CooL:SLiCE project supports sustainable engineering education by leveraging cyber-technology’s role in learning environmentally responsible lifecycle engineering. A multi-institutional team of researchers from Wayne State, Penn State, and Oregon State universities are collaboratively developing the innovative distributed cyberlearning platform to facilitate students’ consideration of the range of human controlled and initiated impacts products have on the natural environment. The learning environment will be an extension of an existing engineering platform developed by the team, which integrates modules for product architectural design and manufacturing and supply chain environmental impact evaluation.

Sustainable design and manufacturing education is in its infancy and learning sustainable product lifecycle design is complex. The complexity stems from conceptualizing the multi-dimensional implications of design choices. Learning about sustainable product lifecycle design requires understanding a variety of technical disciplines, comprehending the numerous purposeful uses of a product, and realizing the interconnections between these considerations. Grasping this complexity requires the multi-stage problem solving skills that are often implemented by engineers in team-based activities. We posit that scaffolding learning activities to balance structured early support and later autonomy will accelerate understanding of these complexities and lead to more sustainable engineered solutions to design problems.

**Evaluation of the CooL:SLiCE Environment**

A constructionist learning environment encourages active experimentation by providing technologies for learners to build their knowledge in concrete interaction with their designs. The CooL:SLiCE cyberlearning environment will supply learning modules that combine critical domain knowledge with concrete design activities. Our project is selecting appropriate tools to support students’ hands-on design activities for three main components: 1) a design platform
with tools for 3D modeling that communicate with a design/analysis interface; 2) a design architecture analysis engine to support benefits and costs of modular design variants and end-of-life considerations; and 3) a manufacturing and supply chain analysis engine to develop parametric models linking design and production information. In addition, a product library will support learners with preprocessed component and assembly models. The portal will interact with these components to serve as the storehouse for the learning modules and interactive tools.

Cyberlearning can be a relatively autonomous student activity. As an autonomous activity, we must compensate for the gap between what a student achieves independently and what that student could achieve with instructor guidance or collaboration (i.e., Vygotsky’s “zone of proximal development”) [6]. Constructionism offers a compelling approach for providing scaffolding for cyberlearning to bridge that gap. Thus, our study investigates the effectiveness of learner engagement with the CooL:SLiCE cyberlearning platform as a complement to instructor guidance. Additionally, our study seeks to determine if this engagement can provide deeper conceptual understandings of the complexity of sustainable product design, as we have posited above. In this line of inquiry, our main focus is to design methods of learning that ensure a learner stays within his or her zone of proximal development in our cyberlearning environment, rather than to concentrate on developing across learners’ cognitive skills [12].

Various aspects of the educational design for the CooL:SLiCE platform will be assessed through an assortment of formative and summative evaluations. First and foremost to our project is the successfulness of students to use and gain knowledge from the modules developed to support learning with the platform. Three core project learning objectives (LOs) for environmentally responsible design include the ability to:

- **LO-1**: Analyze the impacts of product architecture, manufacturing processes, and supply chain decisions on the economic and environmental sustainability of a product;
- **LO-2**: Articulate the impacts of product architecture, manufacturing processes, and supply chain decisions on the economic and environmental sustainability of a product; and
- **LO-3**: Construct product design solutions that address technical requirements, in addition to economic and environmental sustainability goals.

The details of each learning objective appear in Table 1. Constructionism is largely a theoretical model and we use Kolb’s model [13] to operationalize and organize our core learning outcomes. Kolb’s experiential learning framework is an approach where students actively experiment and reflect. In Kolb’s model, knowledge construction is assumed to progress in various stages, which are not necessarily experienced in a specified order. These stages of knowledge construction are:

- Active participation in an experience (Concrete Experience);
- Observations and reflections on the experience (Reflective Observation);
- Formation of abstract concepts and generalizations based on experience and reflections (Abstract Conceptualization); and
- Testing the implications of the concepts (Active Experimentation).

Our three core project learning outcomes, as well as supporting learning outcomes, are mapped to Kolb’s stages of knowledge construction in Table 1.
Learning Outcomes (LO) | Kolb’s Model of Learning
--- | ---
**LO-1: Analyze the impacts of product architecture, manufacturing process, and supply chain decisions on the economic and environmental sustainability of a product.**
1. Learners can distinguish among different product architectures and describe their differences in cost, lead time, and selected environmental impacts (e.g., GHG emissions).
2. Learners can identify the influence of product design variations on manufacturing process- and supply chain-related cost, lead time, and selected environmental impacts.
3. Learners can indicate that the relative importance of product cost, lead time, and selected environmental impacts varies for different stakeholders.
4. Learners can explain that sustainability can be promoted with an understanding of the associated costs and environmental impacts, if handled proactively during the earliest stages of product, process, and supply chain design.
| Abstract conceptualization |

**LO-2: Articulate the impacts of product architecture, manufacturing process, and supply chain decisions on the economic and environmental sustainability of a product.**
1. Learners can estimate cost, lead time, and selected environmental impacts for different product architectures and determine the associated trade-offs due to the different components, processes, and suppliers.
2. Learners can defend the benefits of simultaneously optimizing for the economic and environmental sustainability during concurrent product, process, and supply chain design.
| Reflective observation |

**LO-3: Construct product design solutions that address technical requirements, in addition to economic and environmental sustainability goals.**
1. Learners can construct design solutions for an engineering problem and analyze cost, lead time, and selected environmental impacts to recommend a final design that achieves a goal established for a set of performance measures.
2. Learners can combine the product, process, and supply chain design methods and conceptualize the associated implications in an integrated manner to improve the economic and environmental sustainability of a product design.
| Concrete experience |

| Active experimentation |

Table 1. Mapping of Core Project Learning Outcomes to Kolb’s Model of Learning

The effectiveness of the CooL:SLiCE platform to meet these learning objectives will be evaluated using knowledge-gain assessments to tap into the learner’s awareness of the concepts and level of articulation, as well as the ability to solve problems using the concepts learned. The knowledge-gain assessment questions will be based upon prior work and will cover all four stages in Kolb’s model of learning. The level of knowledge before and after an activity will be assessed by student responses to pre- and post- tests that will be evaluated based on the pre-recorded correct answers. Respondents will include university undergraduate and graduate students attending engineering classes in product design, computer-aided design and manufacturing, sustainable manufacturing, supply chain management, and product lifecycle engineering, product engineering, and also from participants in K-12 summer camp settings.
Comparison of Learner Approaches to Environmentally Responsible Product Design

Resnick has acknowledged that “…providing students with computational tools that support exploration and experimentation….is easier said than done”. He suggests designing computational tools and their context of use, and “doing it well,” requires a good understanding of three intertwined threads of thought: 1) domain knowledge; 2) the computational ideas and paradigms that are the medium of design; and 3) the learner. Understanding the learner (i.e., their preconceptions and expectations) can inform how they might integrate new experiences into their existing conceptual frameworks and how computational media can provide scaffolding to support their process [14]. In this first year of our project, we are conducting a preliminary study to provide insight into the learning experiences and learning contexts of our students taking place within the current (traditional) curriculum offered for environmentally responsible product lifecycle design. This study is being conducted in addition to the assessments described above and its findings will inform the design of the CooL:SLiCE environment, evaluation tools, and metrics.

Study description and context

This preliminary study is oriented by a qualitative approach. Qualitative research interprets data from relatively small numbers of respondents, often by analyzing data collected during long term observations and in depth interviews. For this study, students were asked to respond in writing to 14 questions about their recent environmentally responsible design experience. In total, we collected 74 responses from undergraduate and graduate students who were enrolled in three different engineering classes during the 2014 fall semester across two universities. All students participating in this study received at least some level of instruction in environmentally responsible design during the fall semester and completed projects that required constructing and analyzing sustainable product designs. At the close of the semester, the questionnaires asked students to reflect on this project.

Students were asked to respond to six open-ended (semi-structured) questions. Four of these open-ended questions were crafted to probe the approach students took toward constructing environmentally responsible designs, the complexity of the designs (i.e., lifecycle stages considered), the learning resources students consulted to support their improvements, and the difficulties experienced and/or additional resources (i.e., scaffolding) students thought may have helped their improvements. Two open-ended questions asked students to describe significant and/or surprising aspects of their learning experience. The instrument also included eight questions to probe for students’ understanding of the environmentally responsible design learning objectives (identified for CooL:SLiCE above) by asking students to self-assess their design practice competencies on a 5-point Likert scale (1: no competency at all – 5: complete competency). Students also supplied demographic information about their student status, gender, age, and design-related work experience. Because each course has a different topical orientation and exposes students to varying levels of instruction in environmentally responsible design, our data is grouped, analyzed, and compared by course.

Presented here is a comparison of 42 responses from students who were enrolled in two different classes offered by the Department of Industrial and Systems Engineering at one
university. This interpretation represents 57% of total responses that we have collected (and we plan to analyze the remaining responses in future research). Common to both courses are the inclusion of a hands-on environmentally responsible product design project experience for students. Both courses are considered upper level undergraduate and graduate courses. However, the similarities between these two courses end here.

The 16 respondents from Class A are engineering students who completed a course in the fundamentals of sustainable manufacturing. Ten respondents reported they are undergraduate students (the majority in their 3rd year of study), two students are enrolled in a master’s degree program, and two reported they were doctoral students. The student ages ranged from 19 to 37 years old, with almost half the students falling in the 22-26 age range. Only two respondents reported having any work-related design experience. The central focus of this course is environmental responsibility with major topics including manufacturing systems, sustainability, and lifecycle assessment. Minor topics also included multi-criteria decision making and sustainability measurement. The learning resources provided by the instructor included instructor-led class lectures, textbook readings in sustainable or green manufacturing, student classroom case study presentations and discussions, and guest speakers. Students were also instructed how to use a computer tool/database called OpenLCA to assist in environmental impact analyses. The respondents’ environmentally responsible design experience in this course came from their participation in a team project that called for designing a sustainable manufacturing process for a product. The teams were encouraged to select the product central to their design, instead of the product being chosen for them by the instructor.

Twenty-six engineering students in Class B, a course in integrated product development, participated in this study. A majority of the students in this class reported that they were pursuing a master’s degree in engineering, although four undergraduates and two doctoral also participated in the study. The age of the students in Class B ranged from 22 to 45 year old with majority of the students reporting an age of less than 27 years old. The aim of this class is to familiarize students with current principles and philosophies of product development and realization. Topics covered in this course spanned the product development process (i.e., product specification and conceptual design through manufacturing process development). Learning materials introduced by the instructor for environmentally responsible design consisted of a two-part lecture entitled “Design for Environment.” This lecture was the only class module (out of 10) to focus specifically on environmentally responsible product design, in contrast to Class A where environmental design was the integrating topic of the course. The students received no other resources about environmentally responsible product design from the instructor before asked to individually re-design a hand exerciser the students had previously designed for an earlier class assignment.

A comparison of the respondent group features are depicted in Table 2. Class A is shown to be a more tightly structured learning environment that explicitly led students to a variety of learning support (i.e., scaffolding). An undergraduate respondent from Class A wrote “the classes were really interactive, with a lot of archives, videos, debates, etc.,” a statement, which corroborates this characterization. The learning environment of Class B, on the other hand, can be characterized as an environment of high autonomy with limited instruction and scaffolding for environmentally responsible design.
Class A: Sustainable Manufacturing

Respondent profile:
-16 respondents
-Predominately undergraduates
-Few with design work experience

Environmental design content delivery:
-Major focus integrated of lectures, assigned readings, classroom discussions
-Interactive learning activities
-Computer tool use explicitly encouraged

Environmental design activity:
-Self-selected product
-Team project

Class B: Integrated Product Development

Respondent profile:
-26 respondents
-Predominately graduates
-Many with design work experience

Environmental design content delivery:
-One (of 10) lecture topics, no readings assigned
-Instructor-led lectures
-Computer tool use implicitly encouraged

Environmental design activity:
-Instructor-selected product
-Individual project

Table 2. Comparison of Respondent Group Features

As we compared the distinguishing features of these two groups, we realized that certain contrasting features may define the high and low ends of two learning dimensions (i.e., engagement and autonomy). These two dimensions are of particular interest to our assessment of the CooL:SLiCE environment. Table 3 shows how these features map to these learning dimensions.

<table>
<thead>
<tr>
<th>Class A: Sustainable Manufacturing</th>
<th>Class B: Integrated Product Development</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low autonomy (high scaffolding)</strong></td>
<td><strong>High autonomy (low scaffolding)</strong></td>
</tr>
<tr>
<td>-Learning tightly directed by instructor</td>
<td>-Learning loosely directed by instructor</td>
</tr>
<tr>
<td>-Team-directed projects</td>
<td>-Individual projects</td>
</tr>
<tr>
<td><strong>High engagement</strong></td>
<td><strong>Low engagement</strong></td>
</tr>
<tr>
<td>-Self-selected project focus</td>
<td>-Instructor selected project focus</td>
</tr>
<tr>
<td>-Use of computer tools explicitly encouraged</td>
<td>-Use of computer tools implicitly encouraged</td>
</tr>
<tr>
<td>-Interactive learning activities</td>
<td>-Instructor-led lectures</td>
</tr>
</tbody>
</table>

Table 3. Dimensional Features of Learner Autonomy and Engagement

**Preliminary Study Findings**

*Learner competency in environmentally responsible design*

Our questionnaire included eight questions (identified as 7 through 14 in Tables 4, 5, and 6) to indicate respondents’ self-assessment of their competency to perform different aspects of environmentally responsible design. Respondents were asked to rank an opinion of their competency to statements that addressed the learning and project objectives on a 5-point ordinal scale (1: no competency at all – 5: complete competency). These statements are simplified in Table 4 and are cross-referenced to the learning objectives listed in Table 1.
<table>
<thead>
<tr>
<th>Aspects of Environmental Design Analyses Competency</th>
<th>Learning Objective</th>
<th>Question Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify design alternative for environmental impacts &amp; economic costs</td>
<td>LO-1 (1)</td>
<td>7</td>
</tr>
<tr>
<td>Identify environmental impacts &amp; economic costs for different stakeholders</td>
<td>LO-1 (3)</td>
<td>8</td>
</tr>
<tr>
<td>Explain sustainability promoted by analysis in early design</td>
<td>LO-1 (4)</td>
<td>9</td>
</tr>
<tr>
<td>Analyze &amp; explain economic costs and environmental trade-offs for different design alternatives</td>
<td>LO-2 (1)</td>
<td>10</td>
</tr>
<tr>
<td>Explain and defend benefits of optimizing economic and environmental costs</td>
<td>LO-2 (2)</td>
<td>11</td>
</tr>
<tr>
<td>Construct solutions that analyze economics costs &amp; environmental impact performance measures</td>
<td>LO-3 (1)</td>
<td>12</td>
</tr>
<tr>
<td>Combine &amp; conceptualize integrated product, process, &amp; logistical sustainable designs</td>
<td>LO-3 (2)</td>
<td>13</td>
</tr>
<tr>
<td>Identify implications of my consumer choices on the environment</td>
<td>N/A</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 4. Cross-reference of Design Analyses Competency Questions to Learning Objectives

### Class A

<table>
<thead>
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<th>Question No.</th>
<th>7.</th>
<th>8.</th>
<th>9.</th>
<th>10.</th>
<th>11.</th>
<th>12.</th>
<th>13.</th>
<th>14.</th>
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<td></td>
</tr>
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<td>7%</td>
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</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
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<td>31%</td>
<td>37%</td>
<td>44%</td>
<td>31%</td>
<td>18%</td>
<td>25%</td>
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<td>100%</td>
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<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 5. Class A environmental design practice competency ranking percentages by study question

### Class B

<table>
<thead>
<tr>
<th>Question No.</th>
<th>7.</th>
<th>8.</th>
<th>9.</th>
<th>10.</th>
<th>11.</th>
<th>12.</th>
<th>13.</th>
<th>14.</th>
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</thead>
<tbody>
<tr>
<td>NOT AT ALL</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
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<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>8%</td>
<td>4%</td>
<td>4%</td>
<td>4%</td>
<td>12%</td>
<td>8%</td>
<td>4%</td>
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<tr>
<td>3</td>
<td>42%</td>
<td>31%</td>
<td>36%</td>
<td>34%</td>
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<td>42%</td>
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<tr>
<td>4</td>
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<td>44%</td>
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<td>50%</td>
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<tr>
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</table>

Table 6. Class B environmental design practice competency ranking percentages by study question
The percentage each ranking received for each question is shown by class in Table 5 and 6. For five of the questions (Nos. 7, 9, 10, 11, 12) both groups indicated similar ranges of competency. For question No. 7 both groups chose the mid-range competency rating (3) most frequently. For questions Nos. 9, 10, and 11, the rankings most frequently chosen by both groups were slightly higher (from 3 to 4). No one from either class that selected “No competency at all” for any of the dimensions, apart from two students in Class A who selected “No competency at all” (1) with regard to performance measures (No. 12).

Results for the other three questions (Nos. 8, 13, and 14) were slightly different for Class A and Class B. For question No. 8 (the ranking for the competence to identify environmental/economic impact for different stakeholders), students in Class B most often selected a competency of 4, whereas students in Class A most often selected 3. For question No. 13 (the competency to integrate product, process, and logistical design processes), 31% of Class A indicated a 4 or 5 competency, while 57% of Class B chose a competency rating of 4 or 5. Finally, for question No. 14 (competency to identify the implications of their consumer choices), a larger proportion of students in Class A ranked their competency as high (81% selected 4 or 5) than the students in Class B (54% selected 4 or 5).

This preliminary data shows respondents from Class B rated their competency higher than Class A on two questions (No 8: Identify environmental impacts & economic costs for different stakeholders and No. 13: Combine & conceptualize integrated product, process, & logistical sustainable designs). It was interesting to see this response since Class A had high scaffolding and high engagement. However, Class A indicated a higher competency ranking for the project question (No. 14: Identify implications of my consumer choices on the environment). For the other questions, the two classes’ rankings were similar. It is clear that we cannot make a firm determination with this data. It is our plan to continue our study to understand the relationship between these dimensions.

**Approaches to Environmentally Responsible Design and Design Complexity**

The content of the narrative responses to the open-ended questions was analyzed by theme to compare student approaches towards environmentally responsible product design. The first question asked respondents to describe their environmentally responsible product-related designs and/or design change(s) and the intended environmental impact. In Class B, the majority of design suggestions (78%) discussed changes to product materials, either by substituting more recyclable, recycled, renewable, bio-degradable, less toxic, or more durable materials or by expending a smaller amount of materials. The intent of these changes most often affected end-of-life issues (e.g., reducing the carbon footprint or producing less waste). In Class B, 50% of design changes addressed one (i.e., changing the material or reducing the number of product parts), 38% indicated two, and only 12% considering three or more modifications. One third of Class B students discussed one product lifecycle stage, another third discussed two, and 12% mentioned three or more lifecycle stages. In contrast, the environmental impact improvements in Class A seemed more diverse (e.g., provision of data for more environmentally responsible decision-making, changing package shape, using genetic algorithms to select optimal designs).
Additionally, 56% of Class A projects addressed three or more lifecycle stages. In general, the environmental impact designs from Class A appear more complex.

**Learning Scaffolding**

Our open-ended questions also probed students about their use and desire for learning resources beyond those supplied by their instructors in order to complete their environmentally responsible designs. Because Class A offered more scaffolding than Class B, it was not surprising that only 37% of respondents from Class A indicated a desire for more resources, compared to 50% of the respondents in Class B. Both groups indicated a lack of available environmental data for materials and existing products.

**Concluding Remarks**

A major goal of our study is to better understand the challenges and common issues that arise in the development of a constructionism-based learning environment. We will devise measurements and metrics to describe salient dimensions of constructionism-based classrooms. In this work, we conducted a preliminary study while focusing on learner engagement, different levels of scaffolding, competency, and the depth of conceptual understandings. In accord with a constructionism approach, the CooL:SLiCE learning platform aims to allow customization to facilitate students’ learning needs. In future research, we will investigate if students who use the CooL:SLiCE platform more effectively learn environmentally responsible product design and other sustainable engineering concepts than students who cover the material using more traditional instructional methods. Also, we will conduct a study to explore our hypothesis on differences in the level of needed autonomy that exist between first year undergraduate learners and upper classmen, and that the developed CooL:SLiCE environment can moderate these differences. Throughout the learning module development and delivery process, module improvements will be guided by formative evaluations to assess their quality and clarity as they are being developed and refined. The appropriateness and usability of the CooL:SLiCE system will be assessed through usability analysis.

**References**


