A cyberlearning platform for enhancing undergraduate engineering education in sustainable product design

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Abstract
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Keywords
Constructionism, Cyberlearning, Engineering education, Sustainable product design, Sustainable manufacturing and supply chain analysis

Disciplines
Engineering Education | Industrial Engineering | Sustainability | Systems Engineering

Comments

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A Cyberlearning Platform for Enhancing Undergraduate Engineering Education in Sustainable Product Design

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Abstract

Existing tools for educating undergraduate students about sustainable engineering methods are notably lacking. In particular, these tools are unable to support the assessment of competing objectives in the evaluation of economic, environmental, and social performance across the lifecycle during product design. In an effort to address this deficiency, an interactive, web-based learning environment, a distributed cyberlearning environment, \textit{Constructionism in Learning: Sustainable Life Cycle Engineering} (CooL:SLiCE) has been created. CooL:SLiCE aims to facilitate the consideration of different human controlled/initiated impacts on the natural environment through personalized individual and team-based design activities. Thus, CooL:SLiCE enables constructionist (physical, hands-on) learning in engineering via a virtual platform that allows students to visualize/analyze the effect of changes to product designs, manufacturing processes, and supply chain configurations on sustainability performance. The overall conceptual framework of the CooL:SLiCE platform is discussed. Additionally, the application of constructionism as a pedagogical approach for sustainable engineering education is presented. The framework is designed to facilitate attainment of deeper conceptual understanding in environmentally responsible product design and manufacturing by supplying a set of tools that support a constructivist learning environment. This tool set is based on disparate methodologies from the design, industrial, and manufacturing engineering domains. A team project was undertaken to pilot the CooL:SLiCE platform to aid design and assessment during the sustainable product development process. The pilot project demonstrated the capacity of the CooL:SLiCE platform in the understanding of sustainable product design concepts. This research advances the current educational tools for sustainable product design by integrating three learning modules into a web-based environment developed in the CooL:SLiCE project to provide a platform for learning not currently accessible to engineering educators and students. Future work will mainly focus on using the platform in the classroom settings to investigate its effect on improving student understanding of sustainable life cycle engineering.

Keywords: Constructionism, Cyberlearning, Engineering Education, Sustainable Product Design, Sustainable Manufacturing and Supply Chain Analysis

1. Introduction

Future generations of young engineers must be educated with the knowledge and skills for fulfilling the requirements of sustainable manufacturing from the earliest stages of product design. Universities can encourage a new generation of engineers to advance product manufacturing by providing educational opportunities that enhance their knowledge of sustainable engineering concepts and their ability to
simultaneously evaluate the economic, environmental, and social aspects of their decisions. While universities offer a variety of sustainability-focused undergraduate engineering courses, these often do not make use of appropriate engineering tools to support instruction in sustainable product design and manufacturing (Allen et al., 2008). In particular, the challenge of simultaneously quantifying various sustainability metrics requires the use of multiple tools for evaluating each individual aspect (e.g., life cycle assessment software enables environmental impact analysis). Moreover, while most engineering tools are commercially available, they are expensive, even with educational discounts, and better suited for use by skilled practitioners.

Research suggests that helping students achieve appropriate learning outcomes is a complex process and that there is a need for research that examines the achieved learning level (Hofstein and Lunetta, 2004). Tobin (1990) stated that hands-on experiments and laboratory activities provide opportunities for students to learn by getting involved in a process of constructing knowledge by doing science. Gunstone (1991) opined that it is reasonable to use the laboratory as the setting for students to gain knowledge. Hofstein and Lunetta (2004) suggested that if students were supported with enough time and opportunities for interaction and reflection, meaningful learning would happen in the laboratory. Students are usually engaged, however, in technical activities there are few opportunities to interpret and state their beliefs about the meaning of their laboratory work (Gunstone, 1991). It is therefore crucial to ensure opportunities for encouraging students to ask questions, design inquiries, and suggest hypotheses. Further, it is necessary to provide frequent opportunities for students to reflect and modify their ideas (Barron et al., 1998). In general, in most U.S. schools these types of opportunities do not exist (Tobin, 1990; Polman, 2000). Attesting to this, Kim et al. (2015) observed novices often passively receive existing knowledge and lack opportunities and setting for constructing their knowledge.

From an engineering education perspective, one of the main challenges is the lack of technical materials to provide an appropriate learning environment for students to utilize educational technologies (Ferster, 2014; Raoufi et al., 2017b; Sharma et al., 2017). Existing science and engineering curricula face challenges in addressing technical solutions from a comprehensive perspective that considers economic, environmental, and social aspects of sustainability (Kim et al., 2012; Thota and Dwivedi, 2006; Werner Dankwort et al., 2004). Consequently, engineers in modern manufacturing companies adopt ad hoc, or limited-scope, approaches toward sustainable product and process development, often without appropriate tools or related training. The need for sustainable engineering education motivates finding ways to educate a broad spectrum of students (Zwicker et al., 2014). Efforts have been focused on recruiting new engineering graduates with the potential to achieve technical and defined corporate goals. Moreover, sustainability requires problem-solving skills if it is to continue advancing from a conceptual ideal to a business routine.

Students today may not be attracted to careers in manufacturing engineering due in part to negative perceptions of the impacts of industry on society and the environment. By integrating traditional engineering skills with sustainability concepts, the next generation of students may become more interested in careers in manufacturing engineering (Kim et al., 2012). By studying research engineers’ conceptualization of sustainability, Carew and Mitchell (2008) discovered that different concepts of sustainability exist and that explicit contestation of the variation in the engineering classroom offers opportunities to improve undergraduate sustainability learning and teaching. These authors proposed that rather than supporting a specific tool, sets of actions, or particular outcomes as sustainable, sustainability engineering education needs a diversity of teaching and learning methods that can address the role of values and assumptions in sustainable decision-making (Carew and Mitchell, 2008). The autonomy the learner may have in fulfilling learning activities is one of the ways that instructional design can be modified (Kim et al., 2012). The approach for scaffolding of learning is an important
consider when autonomy of learning is not left to the learner. As a form of constructivist learning theory, constructionism may offer a compelling approach for scaffolding learning.

Constructionism is an approach to learning that engages learners in the design or construction of a tangible artifact in order to cement newly introduced knowledge. Papert and Harrel (1991) defined constructionism as a pedagogical process that encourages learning through constructing, building, or making a product. This approach is cyclical. Learners make a product applying their initial knowledge state which in turn helps them to construct new knowledge and to update their existing knowledge (Ang et al., 2011). Scaffolding (the support that guides students to move progressively toward deeper understanding) and autonomy (being free from reliance on scaffolding) are two key learning aspects inherent to constructionism. Scaffolding makes complex and difficult tasks accessible, manageable, and within a student’s zone of proximal development (Vygotsky, 1978). Scaffolding supports two aspects of students’ learning: how to do the task and why the task should be done that way (Hmelo-Silver et al., 2005). Learners must be provided with autonomy so as to instill the sense that ideas and actions originate from oneself and are one’s own (Deci and Ryan, 1987). Thus, students will act autonomously as they take increased responsibility for their own learning.

One key deficiency to include sustainability in engineering education is that current educational technologies do not support student learning of complex sustainability issues. While the necessary technical elements exist to create such a learning environment, they have not been developed and merged into a single platform. One solution is a simple integrated design tool that can be used by undergraduates to ingrain the concepts of sustainability assessment. By using this design tool, students are able to investigate the inter-twined economic, environmental, and societal impacts of product design changes on the supply chain network and associated manufacturing processes. This tool advances their multi-stage problem solving skills, for both product design and manufacturing analysis, by providing an integrated learning environment with realistic, tangible product design examples. The research presented herein reports on the approach, contributions, and development progress of a collaborative research project entitled Constructionism in Learning: Sustainable Life Cycle Engineering (Cool:SLiCE) (“Cool:SLiCE,” 2018), supported by the U.S. National Science Foundation (NSF). Four universities, i.e., Iowa State University, Oregon State University, Pennsylvania State University, and Wayne State University are working collaboratively on the Cool:SLiCE project to provide an innovative, distributed cyberlearning platform addressing this need. Specifically, the Cool:SLiCE platform integrates the constructionist learning approach in a cyberlearning environment to provide engineering tools to improve understanding of sustainable product design, manufacturing, and analysis.

The Cool:SLiCE project has both technical and educational objectives. While the learning theories supporting development of the Cool:SLiCE platform have been described by Psenka et al. (2017), in this paper, the focus is on the platform’s technical aspects. The technical objective of the Cool:SLiCE platform is to facilitate simultaneous analysis of economic and environmental impacts across materials and manufacturing supply chains by integrating product function modeling and unit manufacturing process modeling. The educational objective of the platform is to support student learning of sustainable life cycle engineering concepts. With this educational objective, the platform has been employed to enhance research understanding of the impacts of cyber-technology on constructivist learning behaviors. As such, the Cool:SLiCE platform supports constructionism – the pedagogical philosophy of learning by doing. In pursuit of the stated educational objective, the impacts of the Cool:SLiCE platform on learning outcomes based on in-class testing will be evaluated and presented in a future publication. As illustrated in Fig. 1, sustainable product design enabled by the Cool:SLiCE platform integrates educational activities with conventional and online engineering methods and tools.
Figure 1. Engineering and education aspects addressed by the CooL:SLiCE platform

The remainder of this paper is as follows. A review of the literature, reporting recent works on tools for sustainable design, sustainable manufacturing processes and system analysis, and sustainable product architecture and supplier selection is provided in Section 2. The development and implementation of the CooL:SLiCE platform and each of the three underlying modules are discussed in greater detail in Section 3. A pilot project that focused on the design of a multicopter attachment is described in Section 4 to demonstrate the use of CooL:SLiCE as a web-based tool to assist students in learning about sustainability analysis during product design. Although the target population of the CooL:SLiCE users is undergraduate students, the pilot project was conducted by three doctoral students who were involved in development of the CooL:SLiCE platform at the three universities, one masters-level industrial engineering graduate student, and one NSF Research Experiences for Undergraduates (REU) engineering student. Thus, researchers at the four universities had an opportunity to test the usability of the platform prior to using it in the classroom settings. Finally, Section 5 discusses the implications of this research on cyberlearning technology to advance engineering education.

2. Limitations of Prior work
Given the objective of this research, three specific areas of extant research are thought to provide a foundation: (1) sustainability tools for engineering design, (2) sustainable manufacturing process and system analysis, and (3) sustainable product architecture and supplier selection. The findings in each of these areas are reviewed in the Supplementary Materials. The limitations of these prior works, vis-à-vis the objectives of the CooL:SLiCE platform, are summarized here.

Prior research has investigated process-based methods decision makers can use to evaluate the cradle-to-gate product life cycle scope from a sustainability perspective (Alsaffar et al., 2016; Eastwood and Haapala, 2015; Gao et al., 2016a, 2016b). In addition to these methods, several life cycle assessment (LCA) software tools have been developed to quantify the environmental impacts of the products. GaBi (Thinkstep, 2013) and SimaPro (PRé Consultants, 2013) are the most commonly used tools to conduct LCA. OpenLCA (GreenDelta GmbH, 2013), an open source LCA tool, is another tool that has gained attention from researchers. Moreover, many simplified LCA tools such as, Sustainable Minds (“Sustainable Minds,“ 2013) and Quantis Suite 2.0 (Quantis, 2013) have been developed; this batch considers simplifications at levels of data input, user interface, and calculation methods, etc. Another category of the LCA tools is CAD-integrated systems to evaluate the
sustainability performance of the product design. In addition to eco-design tools, such as, EcoFit (Jain, 2009), EcoCAD (Cappelli et al., 2006), and EcologiCAD (Leibrecht, 2005), that are recently developed to enhance designers’ capability to assess the environmental impacts during the design phase, commercial tools such as, SolidWorks Sustainability (Dassault Systems, 2013) have been designed to quantify environmental impacts using the CAD model of an intended product.

Rossi et al. (2016) reviewed eco-design methods and tools over the past twenty years to identify the main barriers that restrict their effective use in industrial companies. They found that LCA tools need an expert for their use. One other challenge of these LCA tools is the high level of detailed information to quantify the environmental impacts of the product (Ramani et al., 2010). Although simplified LCA tools are more user friendly, their users still need training to apply them. Moreover, over-simplification causes interpretation reliability issues. Regarding the CAD-integrated tools, two challenges have been identified explaining their limited industrial adoption (Devanathan et al., 2010). First, tools are too qualitative or subjective for designers with limited experience; and second, they are time-consuming, expensive, and not well-integrated with other tools used during the early design phases. In today’s world, it is important to work in a collaborative environment (Khan et al., 2016) to enhance the concurrent design activity. Simplifications in product modeling often lessen the much needed details in results (Rossi et al., 2016). Finally, LCA tools, in general, relate the impacts of manufacturing processes and supply chain directly to the product mass. Thus, the impact of design changes that keep the product mass and/or process parameters unchanged cannot be investigated (Haapala et al., 2013; Raoufi et al., 2017b).

Kremer et al. (2016) identified opportunities for architecting the product design to achieve design for manufacturing, design for remanufacturing, and design for sustainability. They found that one of the research questions in this area is to identify the impact of product architecture and platform decisions on supply chain sustainability measures early in product development. However, a significant gap in the literature exists in capturing the impacts of product design changes on supply chain sustainability performance in terms of economic and environmental responsibility (Ilgin and Gupta, 2010). No mathematical models are available for quantifying the impacts of product architecture designs on supply chain configurations from sustainability perspective (Kremer et al., 2016). Although there have been many studies to derive sustainable supplier selection, relatively few studies have considered the integration of product architecture and supplier chain design for sustainability; most studies have focused on either sustainable product design or sustainable supply chains. Due to this lack of attention to the sustainability coordination between products and supply chains, there are limited relevant tools that are suitable, and none available for direct use for undergraduate engineering education.

As the next generation of practitioners contributing to sustainability, undergraduate students need to realize the implications of their choices by specifically focusing on environmentally responsible designs. Early exposure to product design in a hands-on format with simultaneous use of CAD and sustainability assessment will increase understanding of impacts of product design changes on sustainability performance. Background reviewed herein conveys the motivation and foundation for the cyberlearning platform developed in this research. The next section describes the developed Cool:SLiCE platform and its modules to address the gaps identified in the literature.

3. Overview of the Cool:SLiCE Cyberlearning Platform

The Cool:SLiCE is a collaborative research project to: 1) support the sustainable product design learning in a constructionist mode, 2) provide a distributed cyberlearning environment, 3) provide tools for design and
visualization of products, sustainable supplier architecture and selection, and sustainable manufacturing processes, and 4) offer an integrated platform for analysis of manufacturing processes and supply chains through the development of models that can assess the sustainability performance early in the product design phase.

The constructionist learning paradigm requires the learner to interact with their external environment to gain information and support decision making in the design and “making” of a product. This approach has been shown to support engineering education in general (Kim et al., 2015). Building on this earlier work, it is hypothesized in this research that constructionist learning paradigm can also support design and modification of physical or virtual products, while considering multiple objectives and constraints, as required by sustainable life cycle engineering. The CooL:SLiCE platform provides a comprehensive sustainable product assessment on the basis of energy consumption, carbon footprint (CF), cost, and lead time for different product variants, addressing the limitations noted in the previous section. As shown in Fig. 2, CooL:SLiCE has three main modules, i.e., the Product Design and Visualization module (with a web-based user interface), Manufacturing Process and System Analysis module, and Sustainable Product Architecture and Supplier Selection module (S-PASS). The CooL:SLiCE platform does not assist students in data collection. Students are required to collect data offline for use as input. The tool generates tables and graphs that students can access using MS Excel; these tables and graphs can be used as part of project documentation.

The selection of products for sustainability analysis to engage diverse sets of precollege and university students was the first step in the development of the CooL:SLiCE platform. To support a constructionist learning environment, the products selected should be familiar to the intended audience, and amenable to design personalization. Drones and multicopters have become very familiar to consumers over the past few years, and
therefore, were selected for the platform portal. The following sections describe the purpose and functionality of various portal components.

3.1. Product Design and Visualization Module
The Product Design and Visualization module enables the users to generate simple product models and make product personalization without extensive training. The users can obtain a comprehensive idea of the real product in a virtual (digital) prototype form. Alternatives, concepts, and product assembly compositions being communicated can also be visualized for better understanding. To implement this module, X3DOM (which is a web-version of X3D) is used. The users can generate a simple design model or can use a CAD system to generate more complex product models. The generated design model is first converted to X3D and then to X3DOM for online visualization. To visualize the X3DOM (2014), the standard X3DOM viewer, TeamPlatform 3D Web Viewer (2016) and AutoDesk Forge Viewer APIs (2018) were utilized. To integrate this technology, Java and JavaScript programming languages were used. Using the viewers, the users can investigate their product concepts, for example by using the cross-section option and the explode option (Fig. 3). Viewers facilitate the selection and display of various 3D models made available in the portal. While other CAD systems can be used for these, the main advantage of the Cool::SLiCE visualization module is to provide an integrated cyberlearning platform for sustainable product design (Khan et al., 2017a).

Figure 3. Product visualization (left) and online solid modeler (right) in Cool::SLiCE

The module provides the visualization of design concepts with browsers and an online designer system, which makes the module more accessible to the users. It can also provide a common visualization tool for those users who have access to different CAD systems. Within the module, an existing product model can be modified or a new product model can be generated. A design database supports the learners with preprocessed components and assembly models and a future version of the module will import designs into this database for further processing. The ultimate vision is to implement assembly models and display manufacturing and supply chain data in the portal for rapid, real-time decision making and learning support.

The online solid modeler can also reflect the analysis results from the portal’s two analytic modules. Accordingly, this design module helps users in realizing a product’s architecture and in modifying the product models in accordance with the analysis results. After solid modeling, the online 3D visualizer can store X3D and X3DOM models to be appended to the database. The input connections within the portal are shown in directed arcs between module elements (Fig. 4).
3.2. Manufacturing Process and System Analysis Module

The second module in CooL:SLiCE portal, the Manufacturing Process and System Analysis, provides detailed information about upstream processes and transportation activities in the supply chain, as well as manufacturing and assembly processes to facilitate cost, productivity, and environmental performance assessment based on design information and process settings during early product design. This module enables students to (Raoufi et al., 2017b): 1) evaluate unique design effects on processes and related material/energy inputs and outputs; and 2) modify product and process designs to systematically reduce manufacturing supply chain costs, energy, and environmental impacts for a product of interest. Instead of typical LCA tools, which rely on a mass-based approach, a unit process modeling method described by Sutherland and Gunter (2001) is applied in the CooL:SLiCE Manufacturing Process and System Analysis to quantify process and supply chain performance metrics. This method is composed of three steps: 1) conduct a process inventory, 2) quantify the input and output mass and energy flows, and 3) describe the outputs as a function of inputs. Mathematical models underpinning the Manufacturing Process and System Analysis are implemented as spreadsheet models (MS Excel), and utilize information contained in process and product design databases.

To investigate the environmental (e.g., energy use, carbon footprint) and economic (e.g., lead time, cost) impacts of upstream activities, the Manufacturing Process and System Analysis considers suppliers in different locations. Based on the supply chain configuration, different transportation modes and routes can be assumed for delivering raw materials and intermediate products to manufacturing sites. Student users can investigate the impacts of different transportation modes and compare the performance of different supply chain configurations. Different manufacturing processes can be investigated to understand effects of different design specifications (e.g., material, geometry, size, number of legs, and number of rotors).

The Manufacturing Process and System Analysis follows three main steps for assessing the environmental and economic performance of multicopters.

**Step 1. Part specification:** Design information about the key components of the selected multicopters are identified and provided as inputs. Students then choose the component(s) they want to analyze and then determine the type of raw material and dimensions for the selected component(s) to make their own architecture or to analyze an existing design.

**Step 2. Supply chain configuration:** Students have the opportunity to design different supply chain networks to investigate the effect of selecting suppliers from different global locations. In addition to selecting suppliers, students can determine the transportation modes and routes between supply chain nodes. Thus, they can learn more about the impacts of their decisions on energy use, carbon footprint, lead time, and costs.

**Step 3. Manufacturing process planning:** In the last step, students provide key parameter values (e.g., machining depth of cut or number of mold cavities) for the required Unit Manufacturing Processes (UMPs) to produce the selected component(s). Mathematical models are implemented in spreadsheet form (MS Excel) to calculate the material and energy inputs and outputs for each UMP. These mathematical models utilize
information contained in a material database (for all materials available for analysis), equipment database (containing information for each UMP), and product design information database (for the product variants investigated). This information is then used to complete the manufacturing process and system analysis.

The Manufacturing Process and System Analysis provides the opportunity for learners to assess how changes in product design can affect sustainable manufacturing performance and supply chain network design. This parametric process modeling will be extended to illustrate the connection between the material or process used to make the component and to enhance learner’s understanding. Figure 5 displays how Manufacturing Process and System Analysis assists manufacturing process selection for each new design based on the features of the product and cradle-to-gate energy and carbon footprint reduction in product design considering cost and lead time.

![Figure 5. Framework quantifying life cycle sustainability performance metrics (adapted from (Raoufi et al., 2017a))](image)

### 3.3. Sustainable Product Architecture and Supplier Selection (S-PASS) Module

The third module in the CooL:SLiCE portal, the S-PASS module is a simplified version of the decision-making model proposed by (Ye et al., 2016), that is designed to guide users in the identification of sustainable product architectures and their suppliers. The use of S-PASS within this platform aims to: 1) enhance students’ learning relevant to sustainable product and service design modules, and 2) provide an easy-to-use and effective tool to enable students to determine product architectures and original equipment manufacturer (OEM) suppliers while considering possible environmental impacts.

An overview of S-PASS is illustrated in Fig. 6. The S-PASS employs a matrix propagation system that constructs a series of overlapping matrices to derive a final solution through matrix operations starting from the rows in the initial matrix (i.e., sustainable design requirements) to columns (i.e., product architecture) in the last matrix.

![Figure 6. Overview of S-PASS module](image)

The S-PASS tool uses three overlapping matrices (i.e., a requirement-function matrix, a function-module matrix, and a module-architecture matrix) that utilize a macro-enabled spreadsheet. This matrix system reflects students’ input information regarding new part modules and suppliers corresponding to sustainable design
requirements. Environmental impact is also analyzed through the matrix system to obtain potentially more sustainable product architectures and related suppliers. The S-PASS consists of three main phases.

**Phase 1. Sustainability requirement satisfaction of existing products:** The first phase identifies the relationships between sustainable design requirements and their associated functions, and between functions and module types. Existing products are then evaluated to determine whether the functions and requirements are satisfied with the available modules in those products.

**Phase 2. New module identification and supplier filtering:** In the second phase, for existing module types that do not satisfy the sustainability requirements, alternative modules and their related supplier information are compiled and evaluated with specific attention to environmental indicators.

**Phase 3. Product architecture and supplier selection:** In the third phase, with new modules and suppliers filtered through Phase 2, the functional satisfaction levels of all modules are identified to derive the requirement satisfaction levels of the modules. Then, feasible product architectures configured with these modules are generated to create an initial product architecture set. Final architecture candidates and their suppliers are selected by evaluating the initial architectures vis-à-vis the requirement satisfaction levels.

The matrix system and detailed framework of S-PASS for the above main phases are illustrated in Figs. 7 and 8, respectively. The procedural activities in each phase are processed by the matrix system.

![Figure 7. S-PASS matrix system (adapted from (Ye et al., 2016))](image-url)

The main principle of the matrix system in S-PASS is to convert “To what extent modules satisfy functions” to “To what extent existing product architectures satisfy functions” and “To what extent functions contribute to
achieve requirements” to “To what extent existing products satisfy requirements.” These are easily expressed as matrix multiplications as shown in equations 1 and 2.

\[
M_{\text{function-module}} \times M_{\text{module-architecture}} = M_{\text{function-architecture}}
\]  

\[
M_{\text{requirement-function}} \times M_{\text{function-architecture}} = M_{\text{requirement-architecture}}
\]

An application of the Cool:SLiCE portal is demonstrated in Section 4, using a pilot project. Table 1 summarizes the main objective of each module, along with related inputs and outputs. The Product Design and Visualization module uses parametric design data as an input to display the sectional, assembly, transparent, and exploded views of the product of users. The Manufacturing Process and System Analysis module is used to investigate the product cradle-to-gate life cycle metrics. It considers raw material information, product geometry, transportation routes and modes, and key manufacturing process parameters to quantify environmental (energy use and carbon footprint) and economic (cost and lead time) metrics for user evaluation. The S-PASS module generates sustainable product architectures by using product data inputs to several matrices (e.g., the requirement-function matrix, function-module matrix, and module-architecture matrix), and evaluates the modules and associated suppliers using selected sustainability indicators. The outputs of one module can be used as inputs by other modules, but this process currently proceeds manually.

**Table 1. Main objective, input, and output of each module**

<table>
<thead>
<tr>
<th>Module</th>
<th>Objective</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Design and Visualization</td>
<td>Visually represent the product with sufficient detail</td>
<td>Parametric design data</td>
<td>Sectional, assembly, transparent, and exploded views.</td>
</tr>
<tr>
<td>Manufacturing Process and System Analysis</td>
<td>To integrate environmental and economic impact assessment into manufacturing process flow and supply chain network selection</td>
<td>Raw material data, transportation type and route, part geometry, manufacturing process key parameters</td>
<td>Energy use, carbon footprint, lead time, cost</td>
</tr>
<tr>
<td>Sustainable Product</td>
<td>Determine sustainable product</td>
<td>Requirement-function matrix, function-module</td>
<td>New sustainable product</td>
</tr>
</tbody>
</table>

Figure 8. S-PASS module framework (simplified based on (Ye et al., 2016))
4. Demonstration: Case Study

A pilot project was completed to demonstrate that the three modules developed for the CooL:SLiCE portal can be used as a cyberplatform for learning how to build, analyze, and alter sustainable product designs. Each module was developed independently at one of the three partner universities and the pilot project provided an opportunity to understand how learners might implement the modules to construct product designs and conduct sustainability analyses. The project also aimed to identify the basic elements of a tool set (i.e., construction kit) associated with the cyberplatform necessary to enable engineering students to construct sustainable designs.

The pilot project was undertaken during the summer to provide an opportunity to test the usability of the platform before its introduction as part of a course setting in the fall. A team of six students from five different programs (at the three universities) with expertise in different areas of life cycle engineering was assembled to form a distributed product development team. The team’s three doctoral students were each engaged in development of one of the three CooL:SLiCE modules. The team also included one masters-level industrial engineering graduate student and an NSF Research Experiences for Undergraduates (REU) engineering student.

For the pilot project, the team was tasked with the challenge of designing a virtual prototype of a drone, considering functional requirements and sustainability performance. In addition to the three CooL:SLiCE modules, the “sustainable design construction kit” provided to the team included a kick-off presentation to structure the team design activities with suggested deliverables, broad steps in a design process, and a proposed task timeline. Other tools suggested to the team included a web-based collaboration tool, Slack (www.slack.com), for online discussions to share ideas and document project experiences, and a video chat tool, Skype (www.skype.com), to host and record team meetings. Each team member was asked to create a private channel in Slack as a “design journal” for documenting insights, suggested improvements, new directions, and personal reactions. Other familiar tools already well embedded in the team’s experience were habitually utilized, such as electronic spreadsheets, word processing tools, and email. The team also autonomously chose to adopt a scheduling tool, When Is Good (WhenIsGood.net), to manage the difficulties of scheduling meetings for participants in different time zones. The team also found it useful to construct a spreadsheet displaying a Gantt-style task schedule that was shared by the team via email.

Working as a distributed group, the team brainstormed product suggestions via video Skype discussions and text-based postings to Slack and came to a consensus to design a drone for household garbage pickup. The team chose to design a drone configuration modified with an attachment that would allow it to lift and move a garbage bag of at least 20 lbs. in weight. Members of the team proposed design alternatives by posting a series of hand-sketched drawings (Fig. 9.1) on Slack. These drawings prompted further discussion and three design alternatives were then drawn to scale using the Cool:SLiCE online product design and visualization module. Thus, the team was able to further visualize and reflect on the details of the alternatives and drove the demonstration and finalization of their design alternatives: 1) a four finger-shaped grabber (Fig. 9.2), a two finger-shaped grabber (Fig. 9.3), and a hook (Fig. 9.4).
Next, the Manufacturing Process and System Analysis was used by the team to evoke more detailed ideas in order to specify the raw materials and manufacturing processes for the design of the drone attachments. The Manufacturing Process and System Analysis is programmed as a macro-enabled spreadsheet to estimate the energy consumption and carbon footprint of different raw materials, raw material supply chain transportation configurations, and manufacturing processes (Fig. 10). Manufacturing and supply chain analysis results informed the team’s choice of ABS plastic as the final material for the designed drone attachment.

### Figure 9. Visual representations of design alternatives

![Visual representations of design alternatives](image)

### Figure 10. Manufacturing process and system analysis example

<table>
<thead>
<tr>
<th>Part name</th>
<th>Raw Material</th>
<th>Volume of the part (cm³)</th>
<th>Maximum wall thickness (mm)</th>
<th>Mass (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hook</td>
<td>Acrylonitrile-Butadiene-Styrene</td>
<td>300</td>
<td>2</td>
<td>0.000318</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Type of Destination</th>
<th>Transportation Mode</th>
<th>Average Distance (km)</th>
<th>Upstream CF (kg CO2 eq.)</th>
<th>Transportation CF (kg CO2 eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing, China</td>
<td>Shanghai, China</td>
<td>Connecting City</td>
<td>Rail</td>
<td>1318</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shanghai, China</td>
<td>San Francisco, United States</td>
<td>Connecting City</td>
<td>Deep-Sea Container</td>
<td>9998</td>
<td>106.66</td>
<td>0.10</td>
</tr>
<tr>
<td>San Francisco, United States</td>
<td>Chicago, United States</td>
<td>Manufacturing City</td>
<td>Road</td>
<td>3424</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Values</th>
<th>Energy Consumption (kJ)</th>
<th>Manufacturing CF (kg CO2 eq.)</th>
<th>Unit Manufacturing Process (UMP): Injection Molding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine clamping force</td>
<td>kN</td>
<td>300</td>
<td>349.86</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Number of cavities in the die</td>
<td></td>
<td>5</td>
<td>349.86</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

Finally, the team deployed the S-PASS module to consider sustainable part modules and their associated suppliers to generate candidate drone configurations. The team identified six design requirements (i.e., energy...
efficiency, durability, low environmental impact, use of renewable energy, weight lifting capacity, and ease of control); and eight product functional requirements (i.e., transform energy to torque, rechargeable from external electric power, provide propulsion, protect motor and rotors from external impacts, allow reuse or recycling, provide rechargeable battery, ability to pick up and release objects, and ability to transform solar energy into electric energy). The matrix inputs for each phase were then determined through team discussions guided by the S-PASS module case study. Finally, the requirement-architecture matrix and the supplier-architecture matrix assisted generation of candidate drone architectures (Fig. 11).

![Figure 11. New product architectures and associated suppliers](image)

The CooL:SLiCE platform enabled the team to conduct a comprehensive analysis and suggest the best alternative drone attachment design (Table 2).

**Table 2. Final design summary**

<table>
<thead>
<tr>
<th>CooL:SLiCE Module</th>
<th>Design Considerations</th>
<th>Design Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-PASS</td>
<td>Attachment</td>
<td>Four-fingered gripper</td>
</tr>
<tr>
<td>Manufacturing process and system analysis</td>
<td>Raw material</td>
<td>Acrylonitrile butadiene styrene (ABS)</td>
</tr>
<tr>
<td>Manufacturing process and system analysis</td>
<td>Manufacturing process</td>
<td>Injection molding</td>
</tr>
<tr>
<td>S-PASS</td>
<td>Supplier</td>
<td>Either Supplier 1 or 2</td>
</tr>
<tr>
<td>Manufacturing process and system analysis</td>
<td>Carbon footprint due to supply chain configuration 13.0 g CO₂ eq.</td>
<td></td>
</tr>
<tr>
<td>Manufacturing process and system analysis</td>
<td>Carbon footprint due to manufacturing process 5.96 g CO₂ eq.</td>
<td></td>
</tr>
<tr>
<td>Product Design and visualization</td>
<td>Virtual prototype</td>
<td>Solid models of design alternatives</td>
</tr>
</tbody>
</table>

The pilot project to develop a sustainable product focused on evaluating activities throughout the design process to gauge the feasibility of implementing the CooL:SLiCE platform into classroom settings. The CooL:SLiCE modules were used to create a virtual prototype of a new attachment for a contemporary multicopter. The product design and visualization module was used to visually represent different design alternatives and to communicate ideas among the team members. The manufacturing process and system analysis module was applied to investigate the impacts of the product design alternatives based on the different manufacturing processes and supply chain networks required for production. Finally, the S-PASS module was used to conduct the analysis of the design alternatives and their associated suppliers.

The impressions of the early users of the modules have been generally positive. In particular, pilot project team members were able to utilize the capabilities of the tools across time zones in a collaborative way. The team did

<table>
<thead>
<tr>
<th>Average requirement satisfaction levels for new product architectures</th>
<th>Suppliers selected for new product architectures</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: Energy efficiency 4.7 4.4 4.7</td>
<td>Current Supplier 1 No No No</td>
</tr>
<tr>
<td>R2: Durability 4.8 3.7 4.6</td>
<td>Current Supplier 2 No No No</td>
</tr>
<tr>
<td>R3: Low environmental impact 4.6 4.2 4.7</td>
<td>Current Supplier 3 No No No</td>
</tr>
<tr>
<td>R4: Use of renewable energy 4.8 4.1 4.8</td>
<td>New Supplier 1 Yes Yes Yes</td>
</tr>
<tr>
<td>R5: Weight lifting capacity 4.8 4.0 4.8</td>
<td>New Supplier 2 Yes Yes Yes</td>
</tr>
<tr>
<td>R6: Ease of control 4.8 3.8 4.8</td>
<td>New Supplier 3 No No No</td>
</tr>
<tr>
<td><strong>Average Satisfaction</strong> 4.8 4.0 4.7</td>
<td>*1: very poor – 5: very good</td>
</tr>
</tbody>
</table>

*1: very poor – 5: very good
identify learnings to improve the effectiveness and practicality of CooL:SLiCE in the classroom (Khan et al., 2017b). First, it should be stressed that no analyses should start without first visualizing ideas using the product design and visualization module, since miscommunication will impede the sustainable product design and analysis process. Second, the team found that the manufacturing process and system analysis module needs to be further developed with more raw materials and manufacturing processes to improve its capability in analyzing a variety of creative products. Finally, the team would have benefited from an additional decision-making aid within the S-PASS module. Currently, it requires users to define desired requirements and functions for the intended product designs, but doesn’t offer much support for how to do so; this lack of support could be frustrating to non-expert users.

5. Discussion
Multiple challenges in the existing methods and tools for sustainable product design were identified in Section 2. It was found, for example, that LCA tools focus only on environmental impacts and often require users to have domain expertise, which inhibits the utility of these tools in sustainable design (Rossi et al., 2016). Also, LCA tools require highly detailed process data for accurately quantifying product environmental impacts, adding to their human resource-intensity (Ramani et al., 2010). Further, CAD-integrated LCA tools rely on a mass-based approach, which does not allow high-fidelity analysis of product geometry-related impacts of manufacturing processes and supplier chains (Devanathan et al., 2010; Haapala et al., 2013; Raoufi et al., 2017b). Three modules were developed under the CooL:SLiCE platform, to address these limitations and improve the utility of sustainable design tools for non-expert users. First, the Product Design and Visualization module provides non-expert designers with basic solid modeling capabilities in a web-based platform. It also enables these users to better understand the composition of product assemblies. Next, the Manufacturing Process and System Analysis module enables non-expert analysts to perform manufacturing cost and productivity assessment, in addition to environmental impact analysis, based on the product design (i.e., part geometry and material information). The module incorporates UMP models to eliminate the need for detailed process data. Third, after querying the user about product functional requirements, the S-PASS module determines the relevant product architectures and possible supplier chain configurations. S-PASS is then able to provide non-experts with information about materials- and energy-related carbon footprint, which guides them in selecting the product and supplier chain combination with the lowest environmental impact.

The research presented herein advances current educational tools for assisting non-experts in sustainable product design. The integration of the three developed modules within a web-based environment provides a platform for learning that is not currently accessible to engineering educators and students. CooL:SLiCE can support new approaches and tools to apply constructionist learning within sustainable engineering education, fostering deeper learning of sustainability concepts. By using this learning platform, students can investigate the intertwined economic and environmental impacts of product geometries and architectures, and supplier chain configurations and associated manufacturing processes. Being grounded in constructionist theory, activities using the platform can evoke richer discussions of educational content among students and increase the likelihood of knowledge retention in comparison to traditional, instructor-centric environments (Jawahir et al., 2007; Psenka et al., 2017). Varying the application of the underpinning design and analysis modules can facilitate the investigation of the impacts of different levels of autonomy on student learning. Moreover, by providing an integrated learning environment with realistic, tangible product design examples, the tool can advance multi-stage problem solving skills, for both product design and manufacturing analysis activities.

Through the pilot project presented above, elements of the CooL:SLiCE construction kit were identified that enabled a geographically distributed team to produce drone designs, while considering functional requirements
and sustainability performance. The project demonstrated that the platform can help in the understanding of sustainable product design concepts. Additionally, pilot project team member observations led to enhancements in the CooL:SLiCE cyberplatform for its introduction into classroom settings, including development of module guidelines and product alternatives. The pilot experience also surfaced potential usability improvements (i.e., spreadsheet manipulation in the portal; placement of design visualization vis-à-vis analysis results; and explanatory guidelines). Moreover, among the identified directions for the future development of the platform are to provide a database of drone weight lifting requirements; to develop learning scenarios that integrate all three systems; and to devise playful, exploratory methods for interacting with the modules.

6. Conclusions
As mentioned above, CooL:SLiCE has both technical and educational objectives. The focus of the research presented herein was technical – to facilitate simultaneous analysis of economic and environmental impacts across materials and manufacturing supply chains by integrating product function modeling and unit manufacturing process modeling. The modules developed in this research each can be used in a standalone manner; however, their integration into a single platform enables users to more rapidly design and visualize a product, determine the product architecture and suppliers with the smallest carbon footprint, and evaluate the environmental impacts, lead time, and cost of its manufacture. It is envisioned that the platform can be extended and educational cases can be constructed to also inform and instruct middle and high school students about basic sustainable product engineering concepts. In addition, underlying models could be modified to accommodate more in-depth engineering analysis for more complex, accurate, and industrially-relevant sustainability assessment.

Pursuit of the educational objective of CooL:SLiCE, which will be presented in a follow-on publication, aims to improve student learning of sustainable life cycle engineering concepts, while enhancing research understanding of the impacts of cyber-technology on constructivist learning behaviors. The authors are investigating the effectiveness of the platform by studying whether student users are able to apply the concepts of environmentally responsible product design and sustainable engineering more appropriately than students who learn the material using traditional instruction. As with any educational technology, improvements must be guided by formative evaluations throughout the learning resource development and delivery process to assess quality and clarity.

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References


Highlights
1. Computer tools can support the constructionist learning method in design education
2. Distributed cyberlearning platforms can be used for team-based and individual design
3. Modeling and visualization extended with sustainability analysis in a web platform
4. A manufacturing analysis module enables evaluation of process and supply chain impact
5. A supplier selection module enables identification of the best product architectures