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# Development of Learning Modules for Sustainable Life Cycle Product Design: A Constructionist Approach

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## **Development of learning modules for sustainable life cycle product design: a constructionist approach**

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# **Development of learning modules for sustainable life cycle product design: a constructionist approach**

## **Abstract**

Constructionism is a learning theory in which learners construct their own understanding and knowledge by making a useful product. A cyberlearning environment for sustainable product design and life cycle engineering has been developed based on this approach through a multi-university research project, entitled “Constructionism in Learning: Sustainable Life Cycle Engineering (CooL:SLiCE).” The pedagogic significance of CooL:SLiCE is that it enables better learning within the sustainable engineering domain by utilizing effective learning modules for personalized environmentally responsible product design. The CooL:SLiCE platform provides a web-based portal with three learning modules: 1) Visualization and online computer-aided design (CAD), 2) Sustainable product architecture and supplier selection (S-PASS), and 3) Manufacturing analysis. These modules were first piloted by a team of students from three universities with different engineering backgrounds who were asked to design a sustainable multicopter attachment through the tools developed for a web-based portal. This paper provides a case study of this intercollegiate collaborative pilot project developed from multiple data sources and describes the effectiveness of constructionism to engage students in learning sustainable product design concepts.

## **Introduction**

Sustainable engineering is a process where energy and resources are used in a way that does not compromise the natural environment or limit the ability of the future generations to meet their own needs <sup>[31]</sup>. Over the past several decades, sustainability has become an important issue, especially in the field of engineering; however, sustainable engineering education remains under development due to its broad-encompassing and complex nature. Sustainable engineering curricula delivered solely through lectures limits students’ learning experiences, and the high expectations of students in traditional labs are compromised by, for example, time constraints and limited resources <sup>[24]</sup>. These experiences leave students with little opportunity to construct their own knowledge about the topics covered. Current advances in science, specifically in communication and information technologies, are resulting in a renewed interest in creating physical and virtual hands-on learning activities. One such example is the distributed cyberlearning platform created by a multi-institutional team of researchers (Oregon State University, Pennsylvania State University, Wayne State University, and Iowa State University), named “Constructionism in Learning: Sustainable Life Cycle Engineering (CooL:SLiCE).” The CooL:SLiCE platform, developed under funding from the National Science Foundation (NSF), applies the constructionist theory of learning <sup>[26]</sup> by facilitating the construction of environmentally responsible product designs. This platform supports engineering students’ learning of sustainable design by considering different human controlled/initiated impacts on the natural environment in team-based and personalized design activities. The CooL:SLiCE platform consists of three main modules: 1) Visualization and online computer-aided design (CAD), 2) Sustainable product architecture and supplier selection (S-PASS), and 3) Manufacturing analysis.

In the summer of 2016, a pilot sustainable product design project implemented CooL:SLiCE as a developmental step in this research to gauge the feasibility of the platform’s introduction into real classroom settings. The summer pilot project focused on assessing the different sustainable product design activities by a team of graduate and undergraduate students

from the three different universities in order to apply the findings to the educational design of Cool:SLiCE. The students in this team-based design project had expertise in different life cycle engineering areas and some students had previously participated in the development of different learning modules. The team was tasked with designing an attachment for a multicopter or drone, to be completed during the summer term.

## **Related Literature**

The importance of designing and manufacturing products with smaller environmental and social footprints is especially important for the U.S. market, given its large number of households and high level of consumption of products. The production, consumption, and disposal of consumer products are accelerating in developing countries as well <sup>[1]</sup>, which highlights the necessity for engineering decisions to consider sustainability-related impacts from a product life cycle perspective.

An NSF Mathematics Training in the 21st century (MT21) <sup>[3]</sup> study has demonstrated the necessity of enhancing K-12 student interest in science, technology, engineering, and mathematics (STEM), which the investigators describe as being in a “state of emergency.” By integrating traditional and sustainable engineering skills, the next generation of students may become more interested in careers in engineering <sup>[2]</sup>. Carew and Mitchell discovered that different concepts of sustainability exist within engineering, and this explicit contestation of the conceptual variation in the engineering classroom offers opportunities to improve undergraduate sustainability learning and teaching <sup>[4]</sup>. They suggested engineering education needs to employ a diversity of teaching and learning methods to address the role of values and assumptions in sustainable decision making, rather than supporting a specific tool, sets of actions, or particular outcomes as being sustainable <sup>[4]</sup>. Instructional design can be modified to allow learners to autonomously guide their own sustainable learning activities <sup>[2]</sup>. Constructionism is a variation of the constructivist learning theory that offers a compelling approach to providing autonomy in learning.

The constructionist approach engages learners in the design or construction of a tangible artifact in order to cement new knowledge. Papert defined constructionism as a pedagogical process that encourages learning through constructing, building, or making a product <sup>[5]</sup>. This approach is cyclical. Learners make a product by applying their initial knowledge, which then helps them to construct new knowledge while updating their old knowledge <sup>[6]</sup>. Autonomy is a key learning aspect inherent to constructionism. Thus, students will act autonomously when they take increased responsibility for their own learning. Learners are provided with autonomy so as to instill the sense that ideas and actions originate from oneself and are one’s own <sup>[9]</sup>. However, the provision of scaffolding can make complex and difficult tasks accessible, manageable, and within a student’s zone of proximal development <sup>[7]</sup>. Scaffolding can support two aspects of students’ learning: 1) how to do the task and 2) why the task should be done that way <sup>[8]</sup>.

Laboratory activities provide opportunities for students to learn by getting involved in a process of constructing knowledge by doing science <sup>[10]</sup>. Recent research suggests, however, that helping students to achieve appropriate learning outcomes is a complex process <sup>[11]</sup>. Gunstone supported the use of the laboratory as the setting for students to gain knowledge <sup>[12]</sup>. Hofstein and Lunetta suggested that if students were supported with enough time and opportunities for interaction and reflection, that meaningful learning would happen in the laboratory <sup>[11]</sup>. However, students are usually engaged in technical activities with few opportunities to interpret and state their beliefs about the meaning of their laboratory work <sup>[12]</sup>. It is, therefore, crucial to provide

opportunities that encourage students to ask questions, make design inquiries, and suggest hypotheses. Consequently, it is necessary to provide frequent opportunities for the students to reflect and modify their ideas <sup>[13]</sup>. However, for most universities in the U.S., these types of opportunities do not exist <sup>[10, 14]</sup>. Kim et al. have observed that learners do not have the opportunity to construct knowledge as long as they are treated as novices who are to receive existing knowledge <sup>[15]</sup>.

Design activity in a collaborative environment is an important part of this pilot project. Many researchers have defined collaborative design <sup>[16, 17, 32]</sup>. Yesilbas et al. <sup>[18]</sup> characterized collaborative design as “the coming together of diverse interests and people to achieve a common purpose of developing a product via interactions, information and knowledge sharing, with a certain level of coordination of the variously implemented activities.” Collaborative design environments provide an opportunity for both non-remote and remote designers to work together and share their ideas and thoughts on a common project <sup>[21]</sup>. Effective and efficient collaborative engineering environments are required for collaborators to share their knowledge and work together <sup>[19]</sup>. To provide such environments, collaborators need to have a good perception of the challenges and opportunities of distributed teamwork and collaboration, as well as the technologies that will support a broad range of collaborative work settings <sup>[20]</sup>. Moreover, collaborators need to understand the tools and resources that their collaborators can access, the level of information shared by all collaborators, as well as the shared expectations and objectives, metrics and criteria for evaluation, and how the work is progressing at predetermined milestones <sup>[20]</sup>.

Distributed collaboration (i.e., without face-to-face interactions), may present some drawbacks, such as reduced field of view, restricted use of gestures, time zone differences, understanding collaborators’ level of comprehension, and miscommunication <sup>[21, 22]</sup>. The internet and web-based technologies are the best media for distributed collaborative product environments <sup>[23, 23]</sup>. The “information utility” created by the internet and web-based technologies has many advantages, such as accessibility, usefulness in a wide range of applications, and lower costs <sup>[19]</sup>.

## Case Study

Our collaboration to pilot Cool:SLiCE took place through a distributed team design project, with sub-teams at three universities. Our experience is an encapsulated descriptive case study that may inform the assessment and usability of Cool:SLiCE as a cyberlearning environment for sustainable engineering. We begin with a design scenario (i.e., the general overview) and then describe our collaborative design experience in a six-step process.

*General overview: Drones and multi-copters are very familiar to consumers. While children play with remote controlled toy versions, some adults expect deliveries by drones. Company X is currently selling two types of drones: hexacopters and quadcopters. Due to global regulations regarding the environmental impacts of products and companies, Company X is planning to upgrade its existing products through environmentally responsible design. The eventual design will be used for the household garbage pickup work. The main objective of environmentally responsible drone design at Company X is to determine new product architecture, materials, manufacturing processes, and suppliers while considering their possible environmental impacts. For the household garbage pickup drone, Company X needs to design a new attachment for a contemporary drone to carry a garbage bag. New drones should satisfy design requirements for*

*minimal energy use and reduction in hazardous by-products/pollutants both from the manufacturing system and throughout the drone's useful life. Modules in new drones should be provided by suppliers (for the summer pilot project, students will decide which modules) that are environmentally friendly in their operations (i.e., manufacturing and logistics)."*

The goals of the pilot project are listed as below.

- 
- The challenge was to design and produce a virtual prototype of a new attachment for a contemporary drone.
  - The design activity had to include the following:
    - Visual representation (using the Cool:SLiCE online CAD tool) of at least three design alternatives depicting the design changes
    - Assessment of the design change impacts on manufacturing process and supply chain sustainability performance (measured using energy use, carbon footprint, and supply chain configurations)
    - Trade-off analyses of the design alternatives.
- 

The sub-teams collaboratively agreed to design an attachment for contemporary drones for carrying garbage bags to be produced by Company X.

*Six Step Product Design Process:* The product design in the summer pilot project followed a modified representation of Woodhouse and Ion's <sup>[25]</sup> six steps model (Figure 1) for conceptual product design.

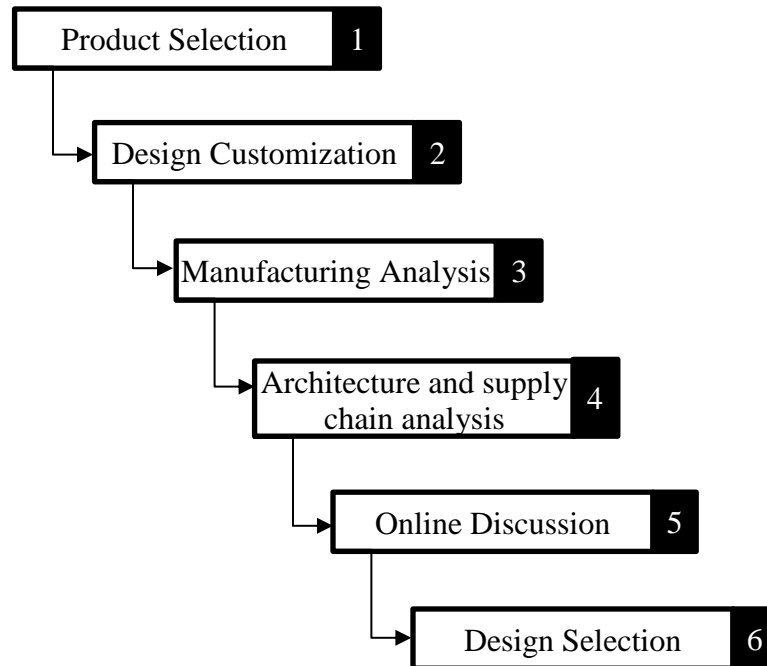


Figure 1. Modified Six Steps model for conceptual product design <sup>[25]</sup>



### I. Product selection:

Because it was an inter-university pilot project, the participants needed to share their thoughts and ideas on a single platform. Hence, Slack<sup>[33]</sup> was chosen as a web-based platform to share work. The student team set their target as the modification of the contemporary drone. The communication through the Slack platform enabled the student team to make the decision to design a drone attachment and that drone should be capable of picking up a garbage bag. After the long discussions, the student sub-teams made the decision to design a drone attachment that could lift at least 20 lbs. of weight.

### II. Design customization

Design customization involves creativity and brainstorming. Hand sketched drawings of drone attachment designs (Figure 2-1) were the outcome of brainstorming, which was the first step of design customization (contemporary drone modification). The second step was to draw the design alternatives to scale using an online CAD system, which is a tool supported by the Cool:SLiCE platform. The student team developed three design alternatives using the CAD system: 1) a four-fingered gripper (Figure 2-2), 2) a two-fingered gripper (Figure 2-3), and a hook-shaped picker (Figure 2-4). From these three design alternatives, the team had to decide on the final design by utilizing the manufacturing analysis module and the supply chain analysis (S-PASS) module to evaluate sustainability performance.

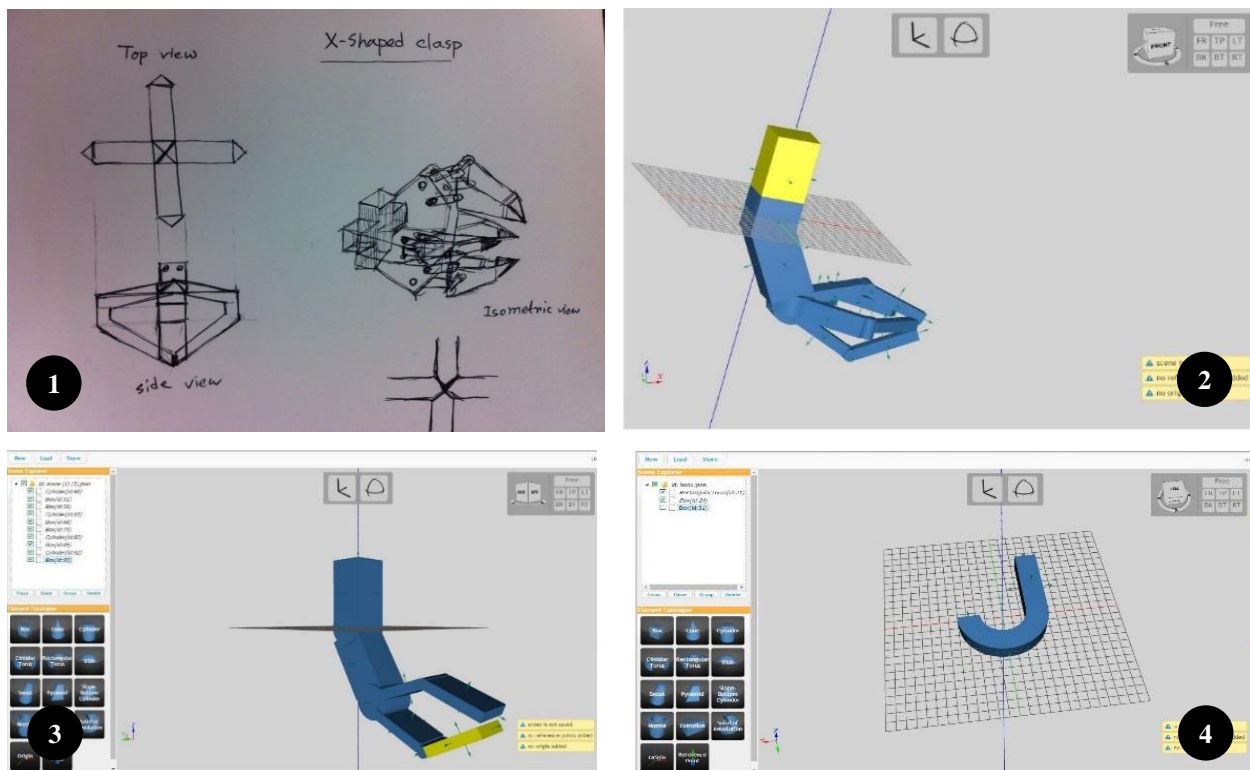


Figure 2. Garbage pickup attachment design alternatives

### III. Manufacturing analysis

Manufacturing analysis can be utilized to identify the most suitable material to be used, according to production time and resource use<sup>[30]</sup>. The Cool:SLiCE manufacturing analysis

module enables the user to choose from among three material options: wood, plastic, and steel. Next, the amount of energy used and the associated carbon footprint due to supply chain network configuration (e.g., supplier, transportation modes and routes, and upstream processes) and manufacturing processes for production of the product being evaluated can be estimated using the manufacturing analysis module.

The manufacturing analysis module was developed by using the mathematical models and applicable equations of different unit manufacturing processes to estimate the energy consumption and the relevant carbon footprint. An example of a mathematical model for calculating the energy consumption of injection molding process, reported by Madan et al. <sup>[28]</sup> is presented below (Eqs. 1-6).

$$E_{total} = \left( \left( \frac{0.75E_{melting} + E_{inj}}{\eta_{inj}} \right) + \left( \frac{E_{reset}}{\eta_{reset}} \right) + \left( \frac{E_{cooling}}{\eta_{cooling}} \right) + \left( \frac{0.25E_{melting}}{\eta_{heater}} \right) \right) \times \left( \frac{(1+\varepsilon+\Delta)n}{\eta_{machine}} \right) + P_b \times t_{cycle} \quad (1)$$

$$E_{melting} = \rho V_{part} \times 10^{-3} \times [C_p(T_{inj} - T_{pol}) + H_f] \quad (2)$$

$$E_{inj} = p_{inj} \times V_{part} \quad (3)$$

$$E_{reset} = 0.25(E_{inj} + E_{cooling} + E_{melting}) \quad (4)$$

$$E_{pack} = 0.75 \times p_{inj} \times V_{part} \times \varepsilon \quad (5)$$

$$E_{cooling} = \frac{H_{cool}}{COP_{carnot}} \quad (6)$$

The Cool:SLiCE platform allows users to apply the manufacturing analysis module as an online spreadsheet. The Cool:SLiCE platform allows users to apply the manufacturing analysis module as an online spreadsheet. The application of the module is demonstrated for evaluating plastic as the raw material to produce the attachment components. Detailed information about supply chain network configuration, part volume and mass, and key manufacturing parameters are presented in Figure 3.

#### IV. Architecture and supply chain analysis

The architecture and supply chain analysis was carried out using the Sustainable Product Architecture and Supplier Selection (S-PASS) tool <sup>[29]</sup>. The S-PASS tool is implemented in the Cool:SLiCE portal by utilizing online spreadsheet technology. The use of S-PASS within this platform aims to: 1) enhance students' class activities 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 with consideration of possible environmental impacts.

An overview of S-PASS is illustrated in Figure 4 shown below. S-PASS employs a matrix propagation system to identify proper product architectures, which constructs and uses three overlapping matrixes (i.e., a requirement-function matrix, a function-module matrix, and a module-architecture matrix) to derive product architecture candidates

through matrix operations starting from design requirements in the initial matrix to product architectures in the last matrix. Students' input regarding new part modules and suppliers that consider sustainable design requirements and proper environmental impact is processed through the matrix system to obtain possible sustainable product architectures and their suppliers.

Manufacturing Analysis Module (Plastic)						
Part Specification						
Part name	Raw Material	Volume of the part (cm³)	Maximum wall thickness (mm)	Mass (tonnes)		
Hook	Acrylonitrile Butadiene Styrene	300	2	0.000318		
Supply Chain Configuration						
From	To	Type of Destination	Transportation Mode	Average Distance (km)	Upstream CF (kg CO2 eq.)	Transportation CF (kg CO2 eq.)
Beijing, China	Shanghai, China	Connecting City	Rail	1318	106.6604975	0.102163224
Shanghai, China	San Francisco, United States	Connecting City	Deep-Sea Container	9998		
San Francisco, United States	Chicago, United States	Manufacturing City	Road	3424		
Manufacturing Process						
Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	Unit Manufacturing Process (UMP): Injection Molding	
Machine clamping force	kN	300	349.8595282	0.0687646		
Number of cavities in the die	-	5				

Figure 3. Screenshot of manufacturing analysis module

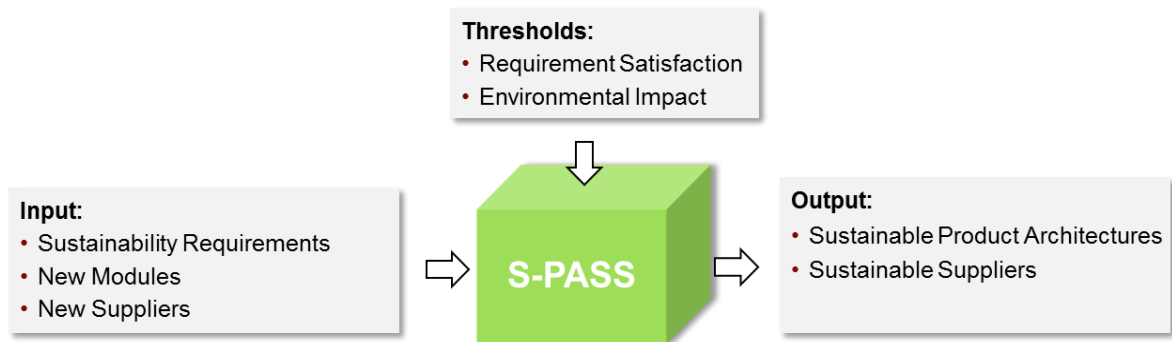


Figure 4. Overview of S-PASS

The method employed by the S-PASS tool consists of three main phases:

#### **Phase 1: Sustainability requirement satisfaction of existing products**

Relationships between sustainable design requirements and their associated functions and between functions and module types are identified. Then, existing products are evaluated to find whether the functions and requirements are satisfied with the available modules in these products.

### Phase 2: New module & supplier filtering

With respect to current module types that do not satisfy the sustainability requirements, alternative modules and their supplier information are compiled and evaluated with specific attention to environmental indicators.

### Phase 3: Product architecture & supplier selection

With new modules and suppliers filtered through Phase 2, functional satisfaction levels of all modules and all possible suppliers are identified. Then, possible product architectures, which can be 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 with the requirement and functional satisfactions.

The team identified six design requirements: 1) energy efficiency, 2) durability, 3) low environmental impact, 4) use of renewable energy, 5) weight lifting capacity, and 6) ease of control. The team also identified eight functional requirements: 1) transform energy to torque, 2) rechargeable from external electric power, 3) propulsion, 4) protection of motor and rotors from external impacts, 4) allow for reuse or recycling, 5) rechargeable battery, 7) ability to pick up and release objects, and 8) ability to transform solar energy into electric energy. The modules identified by the team include the attachment, propeller, upper-shell, lower-shell, knob, propeller shield, and battery cover. The team collaborated to perform tasks that correspond to the three phases of the S-PASS method. To exemplify team interaction, a brief description of Phase 1 is provided below:

The team completed the requirement-function contribution matrix (where 0%: impossible to contribute and 100%: certain to contribute), the requirement-function satisfaction matrix (where 0: no relation and 5: very good in satisfaction), and the module composition matrix (where 0: not used and 1: used) for current products (contemporary drone) (See Figure 5).

Q1) Please estimate to what extent each product function contributes to achieve each environmental sustainability requirement.

	Function							
	F1: Transform energy to torque	F2: Accept recharge from external	F3: Provide propulsion	F4: Protect motors and rotors from	F5: Allow for reuse or recycling	F6: Recharging Battery	F7: Picking-up and releasing objects	F8: Partly transforming solar energy
R1: Energy efficiency	40%	20%	10%	0%	0%	0%	0%	30%
R2: Durability	0%	0%	0%	60%	0%	0%	40%	0%
R3: Low environmental impact	0%	10%	0%	0%	40%	10%	0%	40%
R4: Use of renewable energy	0%	10%	0%	0%	20%	20%	0%	50%
R5: Delivery of a small amount of waste	30%	0%	40%	0%	0%	0%	30%	0%
R6: Easy control	20%	0%	40%	0%	0%	0%	40%	0%

Figure 5. Example of Matrix Inputs for Phase 1 of S-PASS

## V. *S-PASS results*

Through the guidance of the S-PASS procedures, the team derived three new product designs with their associated modules and suppliers (See Figure 6). The S-PASS tool was able to successfully assist the team in deriving new product architectures that satisfy the identified design requirements and functions ( $>4$ , where 1: very poor and 5: very good). The results indicated that

the four-finger shaped architecture provides maximum satisfaction in terms of functionality and design requirements.

1) Average functional satisfaction levels				2) Average requirement satisfaction levels				3) Supplier Selection			
Function	PA1	PA2	PA3	Requirement	PA1	PA 2	PA 3	Supplier	PA1	PA 2	PA 3
F1: Energy Torque	5.0	5.0	5.0	R1: Energy efficiency	4.7	4.4	4.7	E1 (Current)	X	X	X
F2: Recharge	4.0	4.0	4.0	F2: Durability	4.8	3.7	4.6	E2 (Current)	X	X	X
F3: Propulsion	4.5	4.0	4.5	F3: Low environmental impact	4.6	4.2	4.7	E3 (Current)	X	X	X
F4: Protection	4.6	4.2	4.3	F4: Renewable energy	4.8	4.1	4.8	S1 (New)	O	O	O
F5: Recycling	4.3	4.5	4.5	F5: Waste discharge	4.8	4.0	4.8	S2 (New)	O	O	O
F6: Battery	5.0	4.0	5.0	F6: Controllability	4.8	3.8	4.8	S3 (New)	X	X	X
F7: Operation	5.0	3.0	5.0	Average Satisfaction	4.8	4.0	4.7				
F8: Solar Energy	5.0	4.0	5.0								
Average Satisfaction	4.7	4.1	4.7								

PA: Product Architecture

Figure 6. S-PASS Tool Results

#### VI. Online discussion and design selection:

Online discussion and design selection represented the final step in the design activity. As mentioned previously, Slack was utilized as the online collaboration platform for the summer pilot project. Discussions extended from conceptual product design through final product design. After completing the abovementioned analytical steps, the best attachment design (based on the analysis results) was chosen. ABS plastic was chosen as the most suitable material. From the three different architectures, Architecture 1, the four-fingered gripper (Figure 2-2) was chosen to be implemented with the contemporary drone. Two new suppliers were found to have equal acceptability for supplying the drone attachment to Company X. A summary of final design output is shown in Table 1.

Table 1. Final design summary

Item	Result	Tool
Attachment	Four-fingered gripper	S-PASS tool
Raw material	Acrylonitrile butadiene styrene (ABS)	Manufacturing analysis tool
Manufacturing process	Injection molding	Manufacturing analysis tool
Supplier	Either supplier 1 or 2	S-PASS tool
Carbon footprint due to supply chain configuration	13.0 g CO <sub>2</sub> eq.	Manufacturing analysis tool
Carbon footprint due to manufacturing process	5.96 g CO <sub>2</sub> eq.	Manufacturing analysis tool
Virtual prototype	Solid models of design alternatives	Online CAD

## **Observation and Future Implementation**

The following observations were identified based on their design experience piloting Cool:SLiCE:

1. The learning module tools for Cool:SLiCE requires further improvements for their effectiveness and practicality in a classroom setting.
  - Users for the S-PASS tool are required to define desired requirements and functions for their sustainable product designs. A supporting decision making process to guide the team activities might facilitate effective derivation of design requirements and functions.
  - The manufacturing analysis module is designed to handle limited types of materials and manufacturing processes. Hence, improvement is required to enhance its ability to analyze products that require other materials and manufacturing processes.
2. The sequence of product design activities has consequences for deriving collaborative design solutions. Our team first decided to start with the sustainability analyses without drawing and visualizing design alternatives, which slowed down the entire design process. Design visualization can greatly enhance communication. Visualizing the attachment stimulated the cognitive processes <sup>[27]</sup> of the students, which, in turn, drove the students more quickly to the next phase of the design.
3. One of the successes of the pilot project was to enhance the Cool:SLiCE platform so that it could be used in a classroom setting. Some of the enhancements made included: 1) the introduction of manufacturing and supply chain analyses for the drone attachment; 2) the introduction of the calculation of carbon footprint along with the energy consumption; and 3) modifications to increase the user-friendliness of the platform.

As a result of these improvements, the Cool:SLiCE platform was introduced into a classroom setting during the fall 2016 terms at Oregon State University and Wayne State University. This platform helped the students of those classes complete class projects and to understand the notion of sustainable design. Results of this work will be reported at a later time.

## **Concluding Remarks**

One of the best ways to deal with the complexity of sustainable product design is to work in a team comprised of participants with different skill sets. A major aim of the summer pilot project reported herein was to better realize the challenges and common issues that arise in the exercise of a constructionism-based learning environment. Through this summer pilot project, the team realized their capacity in team collaboration, and how that could be improved through web-based tools. The three Cool:SLiCE modules were simultaneously enhanced by the students throughout the summer pilot project. The platform subsequently was introduced in classroom settings and feedback from these students has been collected through a questionnaire. The next step will be the analyses of this data which will be used to improve the Cool:SLiCE platform, accordingly.

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