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Embedding Sustainable Design into a Sophomore Materials Science and Engineering Labs: Use of Materials Selection and Screening and Life Cycle Analysis

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Embedding Sustainable Design into a Sophomore Materials Science and Engineering Laboratory: Use of Materials Selection, Screening and Life Cycle Analysis.

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Abstract: This paper explores the use of materials selection, screening, and Life Cycle Analysis (LCA) processes as part of a sophomore laboratory course at a large R1 university within the department of materials science. This laboratory course is focused on design engineering and sustainable engineering practices. The course was funded by a faculty grant from VentureWell, which enabled the class to focus on design engineering and sustainability. The goal of the design engineering laboratory was to provide students with an understanding of the concepts of materials selection, screening, and LCA processes, while emphasizing the importance of sustainability and design engineering. The laboratory course was structured to provide students with a comprehensive understanding of the topics, while also providing hands-on experience. The laboratory activities were designed to reinforce the lecture material, while also giving students the opportunity to practice the techniques they had learned. The laboratory activities included materials selection and screening, LCA, and design engineering exercises. The findings and conclusions of this paper show that the use of materials selection, screening, and LCA processes was beneficial to the students in the design engineering laboratory course. The use of these techniques allowed students to gain a deeper understanding of the topics and to gain hands-on experience that reinforced the lecture material. The use of these techniques also allowed students to gain an appreciation for the importance of sustainability and design engineering.

Background: As early as the 1970s, there was a call from within the engineering community to include sustainability as an engineering practice within the curriculum [1], with the World Council on Churches calling for education related to "The Future of Man and Society in a World of Science-based Technology". The "Report of the World Commission on Environment and Development" published in 1987 [2] was the first substantial publication outside of environmental engineering for sustainability education. The document was also referred to as "Our Common Future", which was instrumental in bringing sustainable engineering to the forefront of engineering programs. As soon as this report was published, Bell (1987) presented a model process for sustainability education in Canada that began in 1991 with an organization dedicated to promoting sustainability education [3], and Beder described teaching sustainability (environmental awareness) in Australia within an electrical engineering course [4].

During the 1990s, there were multiple publications calling for sustainability education within engineering, a few [5-8] describing specific program integration and practices within engineering departments. Some of these approaches were "high level" and did not require students to complete specific program design aspects. Due to a lack of technology, students were not able to access information and large screening databases at this time, so specific practices for materials selection and screening and LCA analysis were not used.

In 2009, Murphy, et al. conducted surveys of the top one hundred universities with PhD programs in engineering for their sustainability practices, with most (73%) reporting that there were engineering courses related to sustainability for graduate and undergraduate students [9]. Within the courses across all departments, product design and life cycle assessment (LCA) were commonly covered and focused on the use of tools like LCA to look at complex systems and were found primarily in product design and capstone design courses [9]. While LCA was highly ranked in terms of importance and dominance in the courses, Materials and Materials flow were ranked in the lower third of sustainability topics [9]. As these programs were developed, literature was published for toolkits [10], student learning goals and learning environments [11], and calls for social centering of sustainability education [12]. In 2000, ABET moved to a student outcomes-based assessment that included environmental considerations, and in 2017, the Engineering Accreditation Commission (EAC) approved ABET criteria that required accredited programs to ensure students were exposed to social, environmental, and economic considerations [13].

The Engineering for One Planet initiative [14] and the United Nations Sustainable Development Goals [15] both call for the inclusion of sustainable engineering practices in engineering education as an integral part of engineering education. We are calling for a comprehensive integration into the curriculum as well as the creation of toolkits [15-16] and frameworks [14] to guide the process.

In the Department of Materials Science and Engineering at the University of Florida, sustainability processes and practices were not taught until a one-credit required sophomore laboratory course was designed in 2017 to allow students to have experiential learning earlier in the curriculum. The laboratory runs 2 hours a week and was designed to include practices in sustainable engineering. This course was taught to a cohort of students who were also taking courses in Error Analysis & Design Optimization, and a second general materials class and focused on understanding of the materials tetrahedron (structure, properties, processing, performance). In 2018, the PI received a VentureWell faculty grant [17] to redesign the course to include more design thinking, entrepreneurship and product design. The course was designed around "big ideas" in sustainability which would allow for exploration of the concepts embodied in the materials tetrahedron while at the same time exploring through project-based learning sustainability and engineering design thinking practices.

Course Design: The course is designed to address major concepts important to sustainable design and development and incorporate more deeply the role of materials engineering in sustainable design with a focus on polymeric analysis techniques. There are student learning goals for content, professional skills, and technical skills. The course is organized into modules by topic including **Safety**, **Teamwork Practices**, **Engineering Entrepreneurship and Mindset**, **Engineering Design**, **Sustainability**, **Materials Screening and Selection** and the **Design Project**. Before students go into the design project for the semester, they learn the necessary background information for use in their project. Within the Safety module students learn about Standard Operating Procedures (SOPs), Safety Data Sheets (SDS), and American Society for Testing and Materials (ASTM) standards. The Teamwork module includes personality and teamwork tests, understanding and deconstructing materials science related job postings for technical and soft skills, and developing ways of work for teams including Gantt charts, Kanban boards, project management tools and Agile development. Engineering Entrepreneurship and Mindset introduces students to the myths of entrepreneurs and allows them to understand the journey of engineers who started both successful and unsuccessful ventures. Students learn about the importance of the 3C's (Curiosity, Connection, Create Value) for entrepreneurs, and are introduced to an entrepreneur mentor for the project for the year, and generate questions for the mentor related to their journey. The engineering design module uses the Standford d.school framework [18] for design with a particular focus on creating problem statements, stakeholder analysis, and selection of primary and secondary criteria for the product. To get students started, the class participates in a small team project for redesigning a SOLO cup to better meet college students' needs. The Sustainability module starts with readings on sustainability focused on the Hanover Principles of Design [19] which uses a sustainable development matrix for people, planet, and profit. Within this module, students learn how to create system maps, models, and process maps to support the design process. The Materials Screening and Selection Module includes background readings on the materials screening and selection process and use of tools like Ansys CES EduPack [21], the UNESCO Sustainability Guide tools [20], and VentureWell's *Inventing Green: A Toolkit for Sustainable Design* [21].

The Project-Based Learning (PBL) portion of the course lasts about 6-7 weeks and starts with a keynote address by the mentor for this year's project. The readings and activities students have participated in from the first six modules are utilized in the project-based learning design project. The five projects since 2017 have been "Water Pollutant Sensors", "Water Capture Devices", "Headlamp and Flashlights" (COVID at home project), "The Straw Project" and this year's "Fast Fashion". All of these projects are related to global issues in sustainability as addressed by UN sustainability target 4.7 [22] for sustainability education. A roadmap for the main ideas in the project is shown in Figure 1 below and highlights the guiding questions that lead students through the design process.

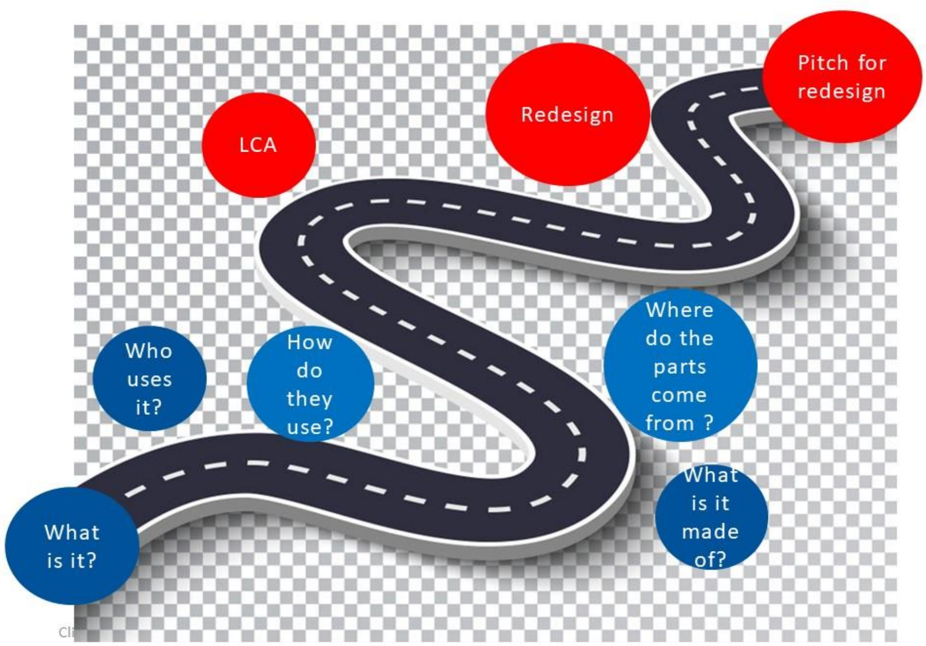


Figure 1. Roadmap of the big ideas for Project-Based Learning within the Sophomore Laboratory class. Blue circles are key activities which build knowledge for the Orange Deliverable activities for the design project.

The keynote speaker creates the compelling "why" for the students and becomes a professional resource for the students as they go into the design project. Students then start to research the background on the materials, product constraints, and stakeholder analysis by answering questions for "What is it?", "Who uses it?" and "How do they use it?". Within these guiding questions, students use the engineering design process and design thinking to start to define the product and its place in the ecosystem. As students build requisite background knowledge, they form teams based on problem statements generated during the background questioning process. While students are conducting background research on the product, they are also learning materials testing and characterization methods for use in determining the material composition of their product. This allows them to later use these materials as a starting point for criteria during the materials screening phase using database tools. Equipment and techniques used by students include Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Optical Microscopy, Tensile and Compression Testing, Differential Scanning Calorimetry (DSC), and Shore, Rockwell, and Vickers Hardness. Students are introduced to new ASTM standards for other tests they may want to conduct as part of the project-based learning.

After teams have deconstructed the product to determine what it is made of (and create a materials inventory and system map), they conduct a Life-Cycle Assessment (LCA) to determine the eco and social footprint of the product, including a carbon, water, and social capital assessment. Life Cycle Assessments are an essential tool for students to understand that materials must be considered beyond their present "product state", to understand where they come from prior to being received and where they go after the product is no longer used or discarded.

Groups then develop a problem statement relative to the issue with the product they want to remediate and then design an experiment or screening process to identify the materials candidates or materials solution for the problem statements. Students are encouraged to focus on materials solutions to the problem statement. The Project-Based Learning (PBL) process is shown below in Figure 2 and shows the approximate iterative cycles for the course. In some of the project-based learning topics, students prototyped designs and tested the revised product ("Water Pollutant Sensors", "Water Capture Devices") and for other topics ("Headlamp and Flashlights", "The Straw Project", and "Fast Fashion") students have made recommendations for materials or processing changes to improve the sustainability of the product.

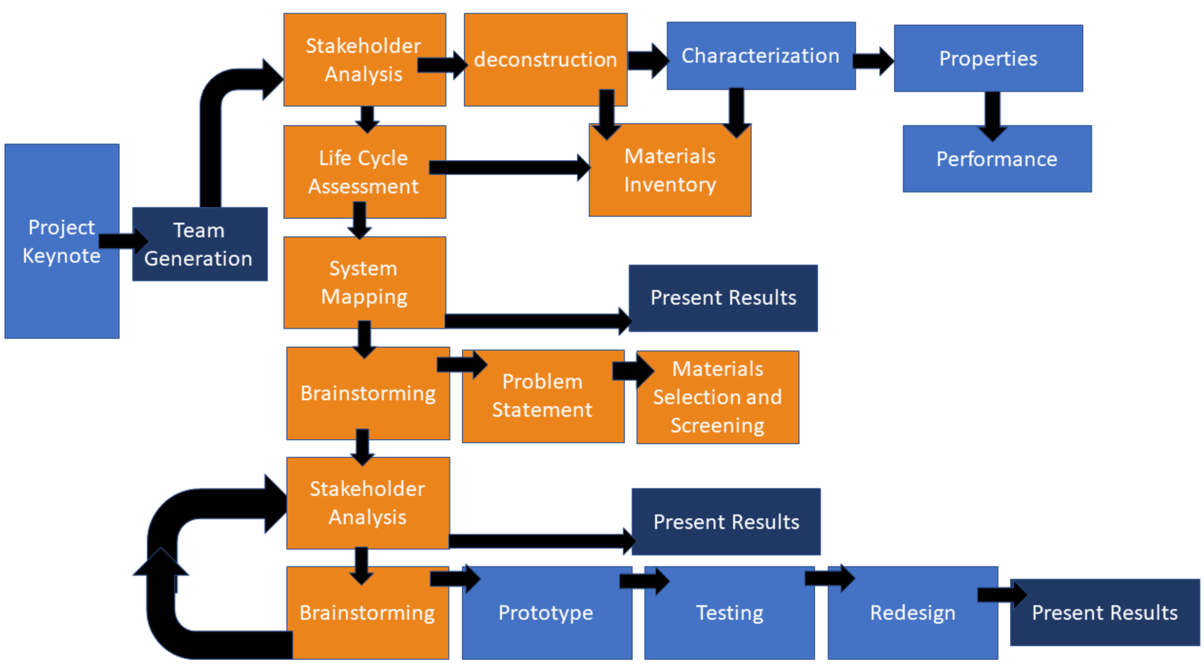


Figure 2. Project-Based Learning process map for student activities within the course. The orange boxes are the activities that support the design process. The blue boxes are the tasks or activities that are conducted and provide material information to the design process.

Examples of student work: Students have been scaffolded in the course teamwork aspects by use of Agile management training, free online project management websites, basic project management and UX design principles, Kanban boards and Gantt charts to build their fluency with engineering project management tools as illustrated in the student chart in Figure 3.

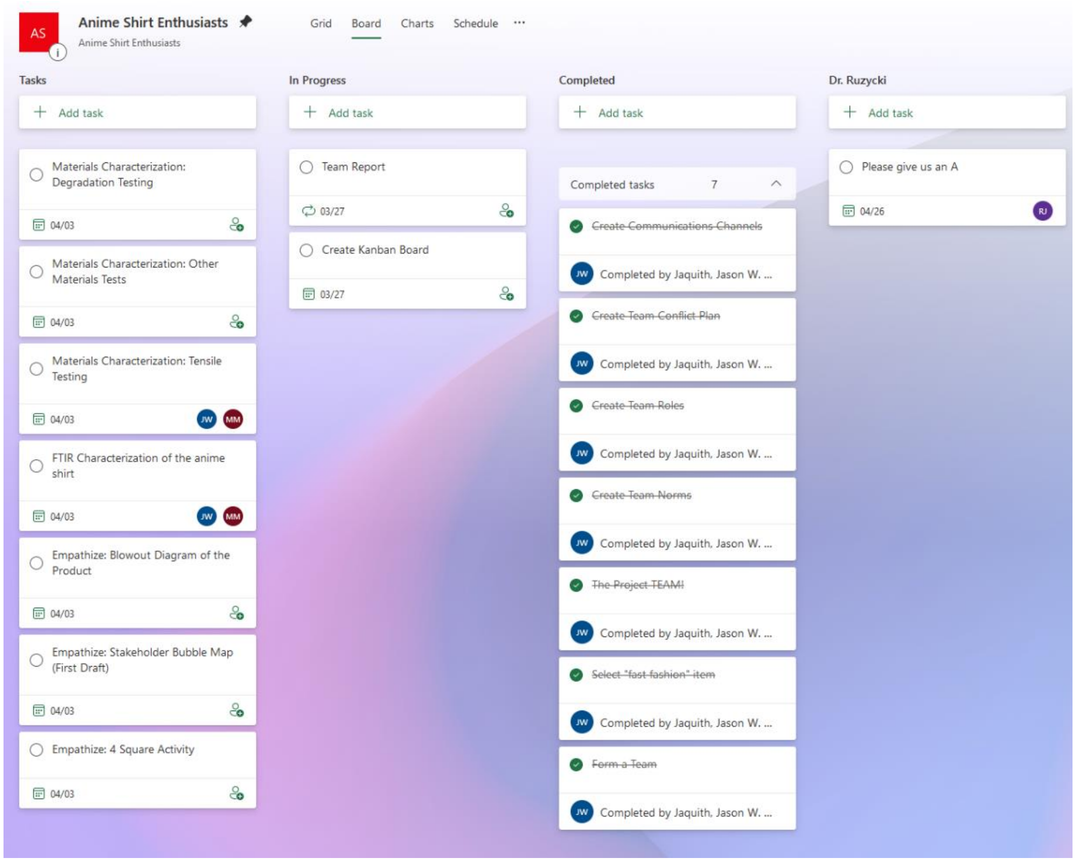


Figure 3. Example of Project Management tool used by students. This is a Kanban Board showing task cards, progress, and task assignment. The board is found in their online project management site.

Additionally, there were scaffolded templates and frameworks for use in the project for students. Below is an example of a People-Profit-Planet (PPP) Canvas as seen in Figure 4 which students would fill out in the early stages of the project to start to collect evidence for use in their design process. This helped students see the main areas for use in problem statement generation and the LCA analysis.

People Who are the stakeholders and what are their needs?	**Planet** What is the product made of? What are the raw stocks used by the product?	**Profit** Where are the general “costs” of the product by category (stocks, transportation, energy…)
What people really “need” the product and what do they need?	How are these stocks sourced and are the practices sustainable? (include human labor and waste streams)	What are the “costs” associated with the end of life of the project?
What people “want” the product and what do they want?	How is the product made, and where is it made? Explain the chain from stocks to store.	What profit is associated with the “branding” of the product? How does the “branding” create value?
What do people “do” with the product when they are finished with them.	Explain if the product “circular” or able to be made into part of a circular stock or supply?	How is profit affected by the end-of-life choices for the product?
What effect does the product have on people? Are there any “harmful” effects from use of the product?	What happens to the product when it is disposed, does it have degradation products that could be harmful to the environment?	How do you think the product could be made at a profit and still benefit planet and people?

Figure 4. People- Profit-Planet Canvas for use by students to collect information.

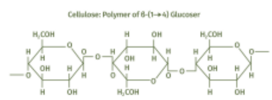
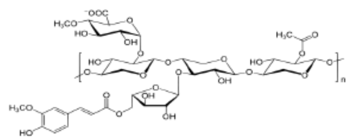
In addition to having scaffolding for the collection of information, documents were created to support students in the learning process for characterization techniques including a document to help students understand how to analyze their straw materials using FTIR. In Figure 5, below is an excerpt from the FTIR supporting document designed to help students identify potential straw composition using peak identification.

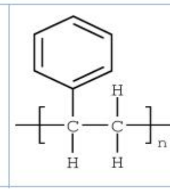
Types of Straws Analyzed:

A. Coconut Drinking Straws
B. Bamboo Fiber Straws
C. Charmed Rainbow Paper Straws
D. Shaumn Biodegradable Sugarcane Straws
E. The Veggie Straws
F. Plastic-less Straws
G. Sustainable Eco Straws

Structure of Common Straw Materials

Plant Material (Coconut, Bamboo, Paper, Sugarcane, Veggie)

Main Components	Structure of Component
Cellulose	
Hemicellulose	

Polystyrene	

FTIR Analysis of Straws

Straw	Type	Expected Material	Expected Bonds	Measured Peaks from tallest to shortest (cm-1)			
				Corresponding Bond			
A	Coconut	Cellulose, hemicellulose, Lignin	O-H, C-H, C-O, C=O, COH, COOH, CH2, CH3	3350	2800	1650	
		aminos	NH3, N-C	N-H, O-H	CH	C=O	
B	Bamboo	Cellulose, hemicellulose, Ligin	O-H, C-H, C-O, C=O, COH, COOH, CH2, CH3	1775	1725	1450	1380
				C=O	C=O	C-H	C-H
C	Paper	Cellulose, hemicellulose, lignin	O-H, C-H, C-O, C=O, COH, COOH, CH2, CH3	3100-3600	2800-3000	1675	
		Filler (clay, CaCO3, talc, TiO2)		O-H	N-H	C=O	
D	Sugarcane	Glucose, cellulose, hemicellulose, lignin	O-H, C-H, C-O, C=O, COH, COOH, CH2, CH3	1750	1450	1380	2900-3000
				C=O	C-H	C-H	O-H, C-H
E	Veggie	Cellulose, hemicellulose, lignin	O-H, C-H, C-O, C=O, COH, COOH, CH2, CH3	2800-3000	1380	1450	
		protein (amino acids), oil (triglycerides)	NH3, N-C, ester	NH3, C-H, O-H	N-C, C-H	C-H	
F	Plastic-less	PLA	ester, CH3, OH, C=O, COH, C-C, carboxyl	1780	1770	1300-1400	2800-3000
		corn starch (glucose)		carboxyl	ester	C-H, O-H	O-H, C-H
G	Phade Eco Straws	PHA	ester, OH, C=O, C-C, COH	1720	1300-1500	2900-3000	
		canola oil		C=O, ester	C-H	O-H, C-H	

Figure 5. FTIR supporting document for the Straw Project

All of these parts of the assignment build towards and support the LCA analysis for students, by taking the product apart in smaller chunks. LCA analysis can often be overwhelming for students since the interactions between and within a product system can be complex. By breaking down the LCA into discovery stages based on the big ideas road map, student teams are able to refine their system map and LCA as they gain and develop new knowledge. Students often system mapped the product twice - once for the original product material, and again for a new proposed material solution to the product. Below in Figure 6 is an example of an LCA system map on a coconut straw. In the diagram, students color coded the different aspects of the LCA including raw materials, manufacturing, use/people, distribution, end-of-life. From this diagram, students can build out an LCA report/one-pager. In addition to the system map, students used both the Ansys CES EduPack [21] Eco-Audit tool and the Social Impact tool to further assess the concepts of how social life cycles impact a product. The Eco-Audit tool in Ansys is limited to material resources, energy, and carbon footprints, but it provides a snapshot to see how changes made to one aspect of the system map can change the LCA analysis.

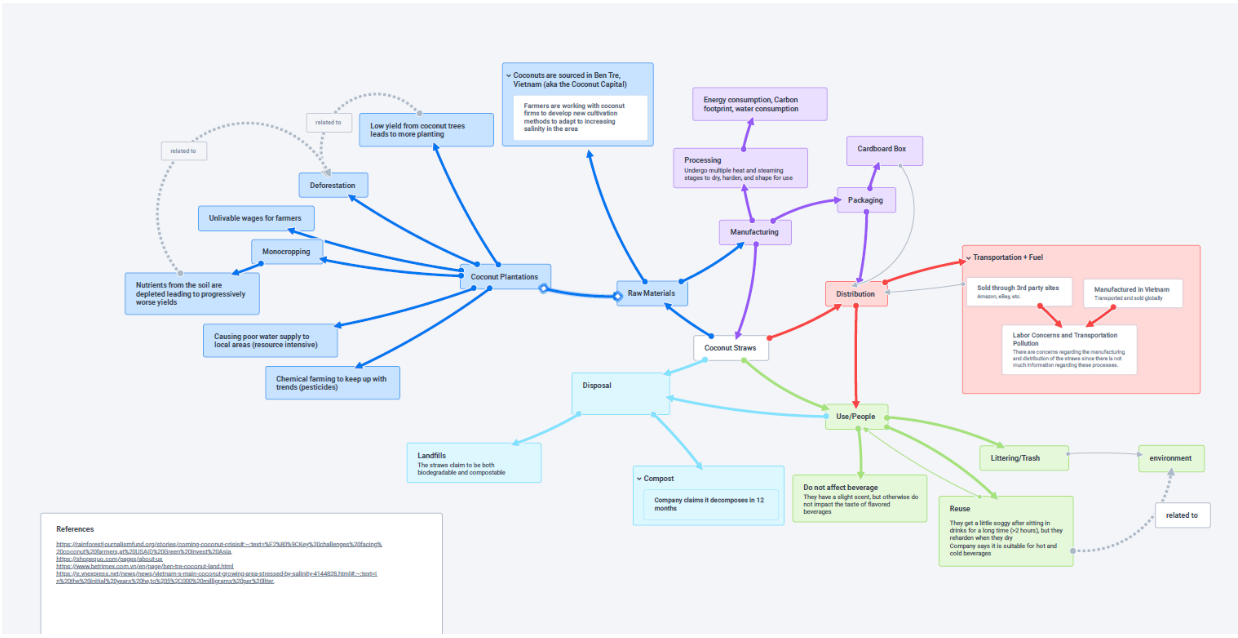


Figure 6. LCA student team analysis for a coconut straw. Students use a system mapping software which allows students to collaborate on one document and add information as they gain knowledge about their material or the process. Full size documents available on request.

In addition to the Ansys Grant tools, students were introduced to LCA tools from the VentureWell Inventing Green Toolkit [23] as well as the Sustainability Guide and Matrix for Sustainable Design created in 2009 by SVID and improved in 2012 and 2017 in a collaboration between Swedish Industrial Design Foundation (SVID) and Green Leap at KTH Royal Institute of Technology in Stockholm [24]. The purpose of introducing multiple tools and guides to students for LCA is to show that each LCA platform has strengths and weaknesses for the design process and that fuller more complete LCA are built out through use of multiple tools with differing sustainability information and focus areas.

Student teams were expected to send in weekly reports to document progress on the project as well as use the project management website to track progress for the project, shown in Figure 7. The purpose of the reports was to create reflective practices in students and ensure they were on track for project completion.

Week 2-3 Report (3/27–4/9)

Team Members: [redacted], [redacted], [redacted], [redacted]

Team Leader: [redacted]

Communication Director: [redacted]

Data Analyst: [redacted]

Engineering Lead: [redacted]

Team Goals for the Week:

- Cut more samples
- Tensile Testing
- Start wetting/drying cycle testing
  - With and without detergent
- FTIR
- Work on reports

Team Contributions:

[redacted]

Description	Date	Time Taken
Blowout Diagram	03/29/23	15 min
FTIR Testing (Half)	03/29/23	20 min
FTIR Sample Preparation	03/29/23	20 min
Tensile Test Sample Prep	03/29/23	45 min
FTIR Testing (half)	04/03/23	20 min
FTIR Report	04/03/23	30 min
Tensile Testing	04/05/23	1.5 hr
Improve and Resubmit Blowout Diagram	04/06/23	20 min

Figure 7. Example student team weekly report snapshot. Students list the group members, the goals for the week, and the accomplishment and time contributions of each member towards those goals. The end of the document (not shown) lists the tasks/goals for the upcoming week.

Students presented results and findings to peers three times during the independent design process, and there were scaffolded slide-deck templates to guide them in these presentations. The first presentation was for the PPP canvas, system map and LCA analysis, the second was to present the problem statement, materials selection and screening process and stakeholder analysis, and the third was for peer feedback on their final pitch deck. During the peer reviews, a simple 4-square rubric was employed as shown below in Figure 8. Peer feedback was aggregated and sent to teams to use as part of their design process. At the end of the semester, students created a business canvas and learned about selling their ideas to others. In lieu of an exam, students presented their final pitch deck to their peers and the main mentor in the program, as well as faculty from the department. The slide deck template had only six slides - to force students to distill the information down to a pitch deck for their design work. The first slide was the problem statement, the second slide was the group approach to the solution, the third slide was for the stakeholder analysis for the original product versus the improved product, the fourth and fifth slide was the design and rationale for the changes to the product, and the last slide was for the funding, which would be needed to move the product to a prototype stage.

4- Square Rubric for feedback

What I like about the presentation	Questions I have about the presentation information
One thing I heard that I wonder about.	I want the presenter to know:

Figure 8. 4-square rubric for project feedback. Students use this during student team presentations to provide feedback to students.

Evaluation: Students routinely fill out the university course evaluations and the students in this course rate the course higher than the college rating over the five years the course has been taught. A separate survey was given to students the year after they took the course to capture how they felt about conceptual growth within the course and if they have applied these learnings in other courses. Below is a breakdown of the main transferrable sustainability concepts for the course. Results for students from the past two years (2021, 2022) taken one year after the course (N=54) were pooled in the data set. Figure 9 illustrates the largest growth in learning occurred for materials selection and screening, use of materials databases for projects, and sustainable engineering/sustainable materials; however, all areas showed growth.

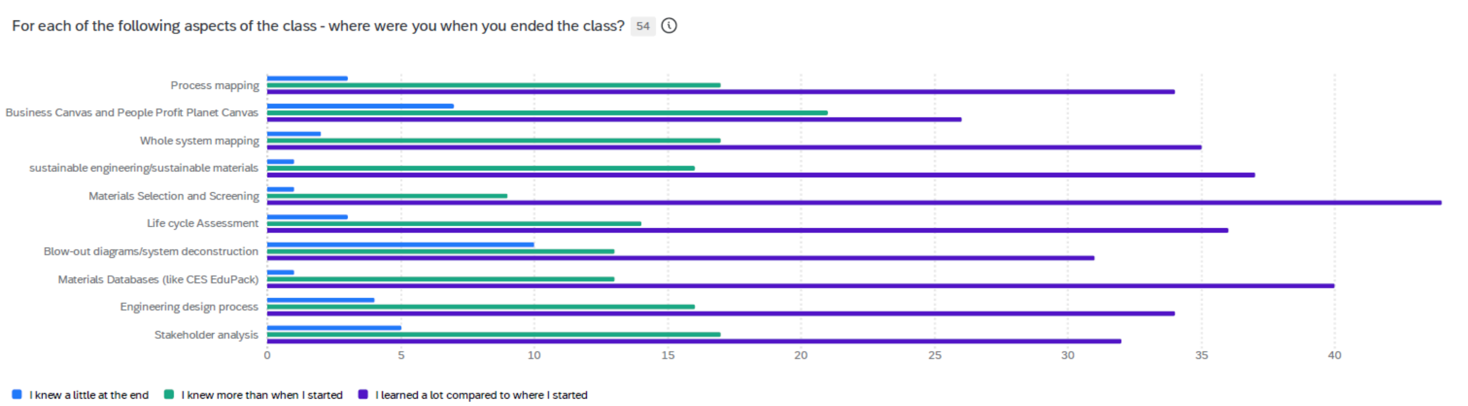


Figure 9. Student responses from survey taken one year after they have taken the class, asking students how what the gain in knowledge was for key transferrable sustainability goals.

Students were asked in the survey what two aspects from the list of key sustainability ideas they were using in other courses and this data is shown in Figure 10. The purpose was to assess what learnings from the course were transferrable to students' current coursework, and if this aligned with where they saw the most growth in knowledge as a result of the course. The aspects were placed into a word cloud plot, where the use of materials databases (in this case Ansys Edupack) is a main tool being applied by students in other courses, likely in the materials screening process.

Figure 10. Student responses from survey taken one year after they have taken the class, asking students what key aspects from the course they are using in current coursework.

Sustainable engineering, life cycle assessment, and the engineering design process were also found to be widely used by students in their current curriculum as evidenced in the word cloud. This aligns well with the findings in Figure 9, for areas of large growth in student learning. It is posited that students may not have an opportunity within the materials science curriculum to revisit some of the other key aspects of sustainability like the life cycle assessment or be asked to take a sustainable approach to a materials problem as part of their upper-level coursework.

As a final question in the survey, students were asked why or even if students should be asked to learn about sustainable engineering practices within their curriculum. Some direct student responses were "*I think it is incredibly important to learn about sustainability and lifecycle analysis since we are entering a much more consumer-conscious era. Everything is moving towards a new form of sustainability and it's important to understand, both as a consumer and an engineer, what each of the sustainability terms mean (biodegradable, sustainably sourced, organic, etc). I really enjoy how useful these concepts are and how they can be applied to any materials selection project since everything has a finite lifetime.*", " *I believe one of the biggest* *mistakes of the past generations has been disregarding the wellbeing of future generations in their decisions. Now every aspect of our society will have to undo the havoc imposed on the Earth from those decisions, including engineers. Hence, I think it is imperative that students learn about sustainable engineering design and materials.*", "*Students should absolutely learn about sustainable engineering design and sustainable materials because understanding the implications of the time, resources and processing of doing any project. Funding is a huge part of any work, but also there is a ecological and societal affect that should be taken into consideration. Having a grasp of sustainable engineering design and sustainable materials provides you with the tools to make informed decisions in large projects later on*." There were no respondents who indicated that the teaching of sustainable engineering practices should not be taught within the materials engineering curriculum.

Summary: This paper explores the use of materials selection, screening, and Life Cycle Analysis (LCA) processes as part of a required sophomore laboratory course at a large R1 university within the department of materials science. This laboratory course is focused on design engineering and sustainable engineering practices. The course was funded by a faculty grant from VentureWell, which enabled the class to focus on design engineering and sustainability. The goal of the design engineering laboratory was to provide students with an understanding of the concepts of materials selection, screening, and LCA processes, while emphasizing the importance of sustainability and design engineering. This course was largely successful in creating students based on the United Nations Sustainable Development goals and Target 4.7 for students to *ensure all learners acquire knowledge and skills needed to promote sustainable development, including among others through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship, and appreciation of cultural diversity and of culture's contribution to sustainable development* [22]. While this course design is only one model, this paper supports the inclusion of such courses to build sustainability education within engineering departments, and especially within materials science and engineering.

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