

## **Integrating Economic and Environmental Sustainability for Undergraduate Education**

**Dr. Pablo K. Cornejo, California State University, Chico**

Pablo K. Cornejo joined the Department of Civil Engineering at California State University, Chico as an Assistant Professor in Fall of 2016. Dr. Cornejo received his Ph.D. and Master's degree in Environmental Engineering from the University of South Florida (USF) and B.S. in Civil Engineering from the University of Colorado at Boulder. His doctoral research focused on the life cycle environmental impacts of wastewater management and resource recovery strategies. After obtaining his Ph.D., he conducted post-doctoral research at the University of Colorado at Boulder, investigating multi-criteria sustainability frameworks to aid decision-making for small drinking water treatment systems. Other research interests include greenhouse gas models for water reuse and desalination facilities; sustainability metrics for integrated resource recovery systems; and sustainable engineering education.

# **Integrating economic and environmental sustainability for undergraduate education**

## **Abstract**

Increasingly, engineers must approach problems considering economically viable, socially just, and environmentally sustainable solutions. This paper describes a new green engineering design course developed at California State University, Chico, which provides students with a sustainability framework to approach engineering problems considering the triple bottom (i.e., economic, social, environmental issues). Through a group project, students applied quantitative environmental and economic assessment tools (i.e., life cycle assessment software and life cycle cost analysis), decision-making strategies, and sensitivity analysis tools to evaluate real-world problems. Students' (n=86) abilities to understand and apply key concepts in the course were evaluated by examining overall performance in the class and performance on group projects. The majority of students performed well in the class (average = 84%, standard deviation = 7%) and on the final group project report (average = 90%, standard deviation = 4%). Future versions of this course could be improved by introducing LCA software earlier in the curriculum and integrating this course as a pre-requisite or co-requisite to a senior capstone. By teaching students an innovative approach to the conventional evaluation-of-alternatives, students were able to propose designs that minimize environmental impacts (e.g., carbon footprint) and provide economically feasible solutions simultaneously. Consequently, this paper highlights a viable teaching model for other universities integrate sustainability into their curriculum.

## **Introduction**

Coastal regions in the United States, such as California, face population growth, urbanization, vulnerability to climate change, and water supply challenges.<sup>1</sup> These stressors have led the State of California to enact an integrated plan to address climate change, which seeks to reduce greenhouse gas emissions (GHGs) by 40% (compared to 1990 levels) by the year 2030.<sup>2</sup> As climate change concerns continue to grow, universities throughout California have taken the lead to further integrate sustainability into the curriculum to prepare the next generation of engineers. In fall of 2016, the Civil Engineering Department at California State University, Chico (Chico State) launched a new green engineering design course to emphasize sustainable decision-making. This course aims to better integrate sustainability education into the College of Engineering, while better serving Northern California and beyond.

Instead of adding a new required course, an existing course (CIVL 302) on engineering risk and economic analysis was transformed to include environmental sustainability. Whereas, the original course emphasized engineering economics, probability, and statistics, the new course was designed to cover triple bottom line decision-making accounting for social, economic, environmental sustainability. This change in course content can be attributed to the Civil Engineering Department's transition to offer more courses in water, sustainability, and environmental engineering. Recently, two new faculty members with backgrounds in environmental engineering were hired, as the department seeks to include an environmental track within the civil engineering degree.

The move to emphasize sustainability in CIVL 302 was also done to better align with: (1) the university's strategic plan for the future and; (2) new Accreditation Board for Engineering and Technology (ABET) program criteria. Similar to other universities around the nation, Chico State has included sustainability in its strategic plan for the future.<sup>3</sup> Specifically, the strategic plan seeks to “create environmentally literate citizens, who embrace sustainability” and are aware that “our individual and collective actions have economic, social, and environmental consequences.”<sup>4</sup> Additionally, new ABET criteria included in 2017-18 accreditation cycle reviews emphasizes sustainability in both civil engineering and environmental engineering criteria. For example, civil engineering criteria emphasize “principles of sustainability in design” and environmental engineering criteria emphasize, “...design [of] environmental engineering systems that include considerations of risk, uncertainty, sustainability, life-cycle principles, and environmental impacts.”<sup>5</sup>

Consequently, the new green engineering design course seeks to prepare students to integrate triple bottom line (social, economic, and environmental sustainability) in evaluating design alternatives to address current and future challenges in a more systematic and holistic way. This paper: (1) describes the green engineering course; (2) highlights the course's integration of group projects designed to address real-world problems; (3) discusses the integration of technology to enhance the learning experience; (4) evaluates students ability to understand and apply triple bottom line decision making strategies when evaluating design alternatives for a group project; and (5) examines instructor insights on improving the course in future semesters.

### **Description of the Course**

The new CIVL 302 course at Chico State provides a foundation for green engineering design. Two sections of the course were offered with 44 students in one section and 42 students in the other section (n=86). This course provides junior undergraduates with tools to approach problem solving considering the triple bottom (i.e., economic, social, environmental impacts), by providing knowledge of quantitative environmental and economic assessment tools, decision-making strategies, risk, sensitivity analysis, and uncertainty analysis. These tools were then applied to real world problems through group projects, emphasizing applied engineering skills, critical thinking, and communication skills. Currently, the only prerequisite for this course is analytic geometry and calculus and the course is required for both civil and mechanical engineering students. The inclusion of civil and mechanical engineering students emphasizes interdisciplinary teamwork, which is beneficial to sustainability-based pedagogy. To meet student learning objectives, both classes were assigned quizzes, homework assignments, exams, and a group project.

Weeks 1-7 of the course focused on introducing sustainability. This includes an introduction to sustainability definitions and challenges, the principles of green engineering, systems thinking, causal loop diagrams, data collection and estimation techniques, sustainability metrics, and life cycle thinking. The primary text used for this portion of the semester was: Matthews, H.S., Hendrickson, C.T., Matthews, D.H. (2015) *Life Cycle Assessment: Quantitative Approaches for Decisions That Matter*.

During the first seven weeks of the course, students were also introduced to life cycle assessment (LCA) and taught how to use LCA software (SimaPro 8). LCA is a central focus for this portion of the course. LCA is a quantitative tool that assesses environmental impacts of a product, process, or system over its useful lifespan. LCA is done in accordance with ISO 14040 guidelines<sup>6</sup> by:

- defining a goal and scope
- compiling a life cycle inventory
- conducting a life cycle impact assessment
- interpreting results

The goal and scope define the goal of the research, the system boundaries, functional unit, and life stages evaluated. The life cycle inventory compiles water, energy and material inputs, as well as, key emissions to air, water, and soil over the system's lifetime. Life cycle impact assessment calculates the environmental impacts of a system based on the life cycle inventory. Interpretation occurs iteratively throughout the study.

Weeks 8-16 focused on key aspects of engineering economics, such as economic decision making, present worth analysis, annual cash flow analysis, rate of return analysis, sensitivity analysis, risk, and uncertainty. This portion of the course provided students with a comprehensive understanding of economic decision making. The book required for this portion of the class was: Newnan, D.G., Eschenbach, T.G., Lavelle, J.P. (2012) *Engineering Economic Analysis*, 11<sup>th</sup> Edition, Oxford University Press.

Life cycle cost analysis (LCCA) is a central focus for this portion of the course. LCCA is used to evaluate costs of engineering designs over its useful lifespan. Key economic concepts covered in the course are in line with concepts required for the fundamental of engineering (FE) exam for Civil Engineers. These concepts include:

- Discounted cash flow (e.g., equivalence, present worth, equivalent annual cost, future worth, and rate of return)
- Cost (e.g., incremental, sunk, estimating techniques)
- Sensitivity analysis (e.g., breakeven, benefit-cost, what-if)
- Uncertainty (e.g., expected value, risk, joint probability)

Tools to conduct triple bottom line decision analysis were covered in week 12. To emphasize triple bottom line decision analysis, students were taught decision-making techniques and exposed to social aspects of sustainability (e.g., technology perceptions, social acceptance, and human health risks). That knowledge can be used in conjunction with LCCA and LCA to make decisions considering the three pillars of sustainability (social, economic, and environmental). Students were exposed to decision analysis strategies, such as the Pugh decision matrix, weighted decision matrix, and analytic hierarchy process. Students were tasked with selecting a decision analysis tool to integrate economic, environmental, and social metrics into their evaluation of alternatives. The course was designed to provide a decision-making framework including tools to assess life cycle environmental impacts, economic impacts, social

considerations, and the integration of these metrics in their final decision analysis. This was primarily done through a group project. Table 1 shows the topics covered throughout the semester.

**Table 1.** Topics covered throughout the semester

Week No.	Topic
Week 1	Syllabus Overview, Sustainability Definitions & Challenges
Week 2	Life Cycle Thinking, Green Engineering, Group Projects
Week 3	Life Cycle Assessment (LCA), Quantitative and Qualitative Methods, Goal and Scope Definition
Week 4	LCA Inventory Analysis, Impact Assessment, Introduction to LCA Software
Week 5	LCA Inventory Analysis, Impact Assessment, Introduction to LCA Software
Week 6	LCA Software and Project Proposal Presentations
Week 7	Review and Exam #1 (10/6)
Week 8	Making Economic Decisions, Engineering Costs and Cost Estimating, Interest and Equivalence
Week 9	Equivalence for Repeated Cash Flows, Present Worth Analysis
Week 10	Present Worth Analysis
Week 11	Annual Cash Flow Analysis, Rate of Return Analysis, Progress Report Due
Week 12	Pugh Decision Matrix, Weighted Decision Matrix, Analytic Hierarchy Process
Week 13	Sensitivity Analysis, Breakeven analysis, What-if analysis
Week 14	Fall Break
Week 15	Risk, Uncertainty, Expected Value, Joint Probability Distribution
Week 16	Final Group Video and Report Due and Review
Week 17	Comprehensive Final

All assignments were designed to help students achieve the following learning objectives:

- Apply social, environmental and economic evaluation techniques to assess the sustainability of engineering alternatives;
- Discuss definitions, challenges, and principles of sustainability, the evolution of engineering design, and green engineering;
- Understand systems thinking, triple bottom line design, and the application of sustainability to design given current local and global challenges;
- Conduct an evaluation of alternatives to evaluate economic and environmental tradeoffs and select the best design;
- Comprehend the multifaceted complexity of engineering problems and the technical, environmental, social, and economic considerations that they require;
- Communicate technical information to technical and/or non-technical audiences using different techniques (e.g., video, small group work, written);
- Recognize that engineering and scientific knowledge is not static and therefore requires continuous life-long learning; and
- Apply professional engineering judgment, decision-making process, statistical tools, life cycle assessment, and life cycle cost analysis to a contemporary issue.

## Integration of Technology

This course integrated clickers, life cycle assessment software (SimaPro 8), and videos as a pedagogical strategy to enhance technology in the classroom. This was done to coincide with Chico State's Strategic Priority No. 3 to use "new technology in learning and teaching" to support high quality learning environments.<sup>4</sup> Clickers were used for in-class quizzes to make the class interactive. Short quizzes were given using clickers to provide real-time feedback on key concepts covered in previous homework, lectures, and readings. This feedback loop was used to gauge student learning and identify topics that require more attention. Clickers were also beneficial to taking attendance and providing participation points. SimaPro 8 was introduced to students to conduct life cycle assessment for their group project. LCA software exposed students to a powerful tool that can quantify life cycle environmental impacts. This software was available for use in a computer lab on campus; however, other free student versions are also available for use (e.g., GaBi education software, water energy sustainability tool). Lastly, students were required to produce a YouTube video explaining the results of their project to the class and the general public. The YouTube videos were done to keep a record of previous projects online, while emphasizing the importance of communicating engineering results to a policy makers, consumers, and clients.

## Description of Group Project

The group project was designed for students to apply the skills acquired throughout the course and accounted for 30% of the students' final grade. Group projects focused on comparing the life cycle environmental impacts, life cycle cost, and social implications of alternative designs applicable to a local sustainability issue of concern. Decision-making and sensitivity analysis were incorporated to evaluate each projects. Each team proposed their own project based on concepts introduced in class (e.g., sustainable development goals, engineering grand challenges, global stressors) or an original idea. Collaboration with a client (e.g., government, consulting company, non-profit organization, and researcher) was encouraged, but not required. Table 2 highlights the project deliverables.

**Table 2.** Summary of Deliverables for your Sustainable Design Project

Deliverable Name	Summary of Deliverable (% of total grade)
Form Groups	Form groups of 5 people. Teams must be interdisciplinary including at least 2 members from a different discipline than your own. (0%)
Project Pre-Approval	Decide on a group project and get pre-approval on the project from instructor. This should be done by submitting a brief description of your proposed project. (0%)
Project Proposal	Project proposal presentation defining problem, identifying alternatives, defining sustainability metrics and defining project management tasks (5%).
Progress Report	Written progress report including items from project proposal, life cycle assessment (LCA) and life cycle cost analysis (LCCA). Project at 70% completion (10%).
Final Report	The final report should be no more than 12 pages including all completed tasks including progress report, sensitivity analysis, evaluation-of-alternatives and final recommendation (10%).
Group Video	The group video should explain the findings of your project to the general public. Video should be 6-8 minutes long and all students should present part of the video uploaded to YouTube (5%).

The final choice of a project was made in consultation with the instructor to ensure proper scope and feasibility. The deliverables for the group project include: (1) forming a group, (2) project pre-approval (3) project proposal; (4) progress report; (5) final report and (6) an individual newsletter or group video (all students opted to do the group video). The group project also included a peer-evaluation component to ensure accountability and fair grading of individual and group efforts.

Upon forming groups and getting pre-approval for a project idea, groups were tasked with the project proposal assignment. This assignment entails a presentation including: (1) problem definition, need the project addresses, identification of study design parameters (2) generation of alternatives to be evaluated (3) Identification of key sustainability metrics (social, environmental, economic) (4) Description of key project management tasks including a timeline for key deliverables at each milestone through to the final presentation.

The progress report included a written update on the progress on the project. The majority of the project was expected to be completed (~70%) at this stage in the semester (Week 11). The progress report included: (1) items from the project proposal (2) life cycle assessment and life cycle cost analysis results of alternatives assessed. This was followed by a meeting with the instructor during office hours to ensure groups were on task to finish the assignment by the end of the semester.

The last two assignments included the final report and group video. The final report included a 12-page report with: (1) Items from the project proposal (2) Items from the progress report (3) A sensitivity or uncertainty analysis of cost or environmental impacts (4) A final evaluation-of-alternatives including social, economic, and environmental impacts (5) A final design recommendation. Lastly, the group video summarized project findings. The video was shown in class and posted on YouTube including key tables, figures, and/or pictures as needed. A peer evaluation form was used to ensure equitable student participation, allowing students to grade individual performance of each team member, including themselves.

Group projects included a wide range of topics including:

- Energy storage methods (Lead acid batteries versus inertial energy storage)
- Street lighting for downtown Chico, CA (varying light bulbs and energy sources)
- Modern car engine alternatives (gas engine versus electric motor)
- Biofiltration systems for stormwater runoff (Bioswale versus bioretention basin)
- Irrigation systems for an urban farm (drip irrigation versus spray sprinklers)
- Fertilizers (synthetic versus organic)
- Food production systems (aquaponics versus conventional farming, household aquaponics systems with alternative energy sources, hydroponics versus aquaponics)
- Material analysis (alternative materials versus conventional materials for roads, decking, and storage dams)
- Food waste handling (composting versus food waste to glass versus food waste to landfill on campus, on-site composting versus municipal waste disposal at brewery)

Each deliverable was evaluated using a rubric to assess the group’s understanding of key concepts in the course. Table 3 shows an example of a rubric used to grade the final report for the group project. A similar rubric was used to grade the group video. The rubric includes technical content (70%) and preparation and organization (30%).

**Table 3.** Grading rubric for the final report.

	Grading Guide		
	Poor	Fair	Good
<b>Technical Content (70 points)</b>			
Problem/Need/Study Design Parameters	0-4	5-7	8-10
Alternatives Assessed and Sustainability Metrics Evaluated	0-4	5-7	8-10
Comparison of Life Cycle Inventory & Life Cycle Assessment Results	0-4	5-7	8-10
Comparison of Life Cycle Cost	0-4	5-7	8-10
Sensitivity or Uncertainty Analysis	0-4	5-7	8-10
Triple Bottom Line Evaluation of Alternative and Final Recommendation	0-4	5-7	8-10
Project Management, Calculations	0-4	5-7	8-10
<b>Preparation and Organization (30 points)</b>			
Evidence of Effort & Organization	0-4	5-7	8-10
Legible and Appropriate Information	0-4	5-7	8-10
Variety of Visual Aids (graphics, tables)	0-1	2-3	8-10
Technical writing style, professionalism	0-1	2-3	8-10

## Results – Overall grades in the course

Tables 4 shows the grades for key assignments in the green engineering design course for both sections. Average, maximum, minimum and standard deviation grades are shown as percentages for both Section 01 and 02 (n=84). The average final grade was 84%, where most grades fell in the B range (80-90%), indicating a high success rate in the course.

**Table 4.** Grades for Section 01 and 02 of the green engineering design course, expressed as percentages (n=84).

	Midterm	HW	Project Proposal	Progress Report	Video	Final Report	Individual Participation	Final Exam	Final Grade
Avg	90	82	89	87	96	90	96	71	84
Max	102	99	98	97	100	96	100	100	98
Min	68	40	44	62	86	82	60	40	64
Std Dev	8	16	11	10	4	4	11	14	7

On exams, students did better on the midterm, which covered environmental sustainability topics (average grade 90%) and worse on the comprehensive final (average 71%), which had a larger focus on engineering economics. Average homework grades were 82%, with a minimum and maximum homework performance of 40% and 99%, respectively. Grades for project activities ranged from 87-96%. On average, project proposal (89%) and progress reports (87%) were slightly lower than average grades for the final video deliverable (96%) and final reports (90%).



This highlights that having checks throughout the semester using oral presentations, written communication, faculty-student meetings and videos may have allowed students to revisit materials and improve their grades over the course of the semester for the final deliverables. Average individual participation grades were high (96%) based on student peer evaluations. The individual participation grade allowed students to evaluate each other on project performance to ensure accountability of all teammates. Consequently, individual group members did not all received the same grade on the project.

## Results - Group Project

Table 5 shows the results for the final report for 17 groups in two sections of the course. Overall students performed well in both: (1) technical content (62 out of 70 points on average) and (2) preparation and organization (28 out of 30 points on average). The average grade on final reports was 90% with grades ranging from 82% to 96%. All students got a 70% or better on the group project, indicating a high success rate for project completion. Generally, students did a good job identifying an environmental problem (9.4 out of 10 points on average), alternatives to assess the problem and sustainability metrics spanning social, economic, and environmental impacts to evaluate the alternatives (9.3 out of 10 points on average). Additionally, student groups generally did well compiling a life cycle inventory data and conducting a life cycle assessment (9.2 out of 10 points on average) within the time constraints of a semester long group project. Furthermore, student groups had high scores (9.8 out of 10 points on average) for the comparison of life cycle costs using net present worth, equivalent uniform annual worth, or incremental rate of return economic analysis techniques for evaluating alternatives. Scores on project management, evidence of effort and organization, legible and appropriate information, variety of visual aids, were also high.

**Table 5.** Grading outcomes for group project final report

	Results			
	Ave	Min	Max	Std Dev
Technical Content				
Problem/Need/Study Design Parameters	9.4	5.0	10.0	1.4
Alternatives Assessed and Sustainability Metrics Evaluated	9.3	5.0	10.0	1.3
Comparison of Life Cycle Inventory & Life Cycle Assessment Results	9.2	7.0	10.0	1.1
Comparison of Life Cycle Cost	9.8	8.0	10.0	0.6
Sensitivity or Uncertainty Analysis	6.9	3.0	10.0	2.5
Triple Bottom Line Evaluation of Alternative and Final Recommendation	8.5	5.0	10.0	1.7
Project Management, Calculations	9.5	5.0	10.0	1.3
Total Score out of 70:	62.2	48.0	68.0	4.6
Preparation and Organization				
Evidence of Effort & Organization	9.2	7.0	10.0	1.1
Legible and Appropriate Information	9.6	8.0	10.0	0.7
Variety of Visual Aids (graphics, tables)	4.9	3.0	5.0	0.5
Technical writing style, professionalism	4.2	3.0	5.0	1.0
Total Score out of 30:	27.9	23.0	30.0	2.0
Final Report Grade (%):	90%	82%	96%	4%

Areas that require improvement include the sensitivity or uncertainty analysis (6.9 out of 10 points on average) and the integration of social metrics into the triple bottom line decision analysis (8.5 out of 10 points on average). The criteria with the lowest scores were the sensitivity or uncertainty analysis portion of the project. Some groups failed to include a sensitivity or uncertainty analysis. Other groups discussed sensitivity or uncertainty of results, but did not show findings using techniques introduced in class (e.g., breakeven analysis, what-if analysis, standard deviation, joint probability distribution). For the triple bottom line evaluation, most groups did well discussing the triple bottom line and defining social, economic, and environmental metrics. However, some groups failed to integrate social, economic, and environmental metrics in a decision matrix for their final design recommendation. Additionally, the integration of social metrics proved to be a particular challenge for undergraduate engineering students. The integration of social metrics in the decision making process is a particular challenge for engineering students that haven't been exposed to qualitative assessment strategies from the social sciences or concepts of social sustainability earlier in their undergraduate education.

### **Instructor Insights and Future Improvements**

Most students seemed content with the course and excited to have sustainability integrated into the curriculum. During informal conversations, students expressed that they were happy that their traditional engineering economics course was being converted into a course covering engineering sustainability and economics. The course covered a lot of material in one semester that could be easily be taught in two separate classes; however, this could take away from the intersectional nature of thinking about the social, environmental, and economic aspects of sustainability and triple bottom line decision analysis. As we face growing populations and limited resources, innovative approaches decision analysis will be important for engineers of the 21<sup>st</sup> century and beyond.

A key challenge in the course was the integration of life cycle assessment (LCA) software into the curriculum due to (1) accessibility to the proprietary software and (2) a lack of previous experience with the software. SimaPro 8 is proprietary software that was available to students in one computer laboratory. Unfortunately, online versions of this software were not readily available and some students expressed frustrations in accessing the laboratory. Future versions of the course could include free software and tools for general LCA use (e.g., GaBi Educational version, USEPA's TRACI – Tool for Reduction and Assessment of Chemical and Other Environmental Impacts) or free software for LCA of wastewater and water treatment systems (e.g., WESTWeb - Water Energy Sustainability Tool). Additionally, introducing SimaPro 8 or other LCA software to students earlier in the curriculum (e.g., a lower division computing course) could be beneficial. Another option would be to include a laboratory component to the class, so that students gain more experience with LCA.

In future offerings of the course, CIVL 302 could be taught in its original form where students self-select projects and a new form, where a main theme is implemented with pre-selected projects. There are advantages and disadvantages to allowing students to pick their own projects or narrowing the scope of projects with data readily available. An advantage of allowing students

to select their own projects is that they take ownership over a topic of interest. Previous studies have shown that autonomy in learning is motivating and motivation leads to improved learning outcomes.<sup>7</sup> However, the challenge of allowing students to select their own projects is that students may spend a lot of time searching for relevant data. Data collection is a key challenge with LCA that can be time-intensive and labor-intensive. At the same time, data collection requires critical thinking skills, independent research, and experiential learning that can be applied to a capstone course.

In the new form of the course, input data to conduct the LCA and LCCA would be given to students, so they do not have to spend as much time researching data sources. For example, all projects could focus on the water-energy-food nexus or campus sustainability issues with predefined data readily available. Limiting the scope to projects with data readily available could improve data accuracy and reduce time spent on data collection. This could potentially provide students with the opportunity to focus more on learning LCA software, instead of focusing on data collection. This represents a trade-off that the instructor should consider when deciding whether to have pre-selected projects with data available or allowing for autonomy in project selection. Having 2-3 pre-selected projects with an innovative component integrated, could incorporate the creativity needed to motivate students, while ensuring data consistency, accuracy, and verification of results. Additionally, teaching the course in two different forms would allow for comparison of two sections to determine whether the new version makes a difference on common performance metrics (e.g., exams, projects, homework, etc.) and/or student perceptions of the group project.

Lastly, the Civil Engineering Department at Chico State is considering the integration of this course with a capstone class, as a pre-requisite or co-requisite. Life cycle assessment, life cycle cost analysis, and decision analysis are tools that could be integrated into a capstone design project, to enhance the design experience. This would better prepare engineering students to tackle problems and engineering solutions, accounting for environmental, economic, and social dimensions of sustainability. Future studies, could explore longitudinal data and student reflections on how this course helped shape senior capstone design projects in terms of both scope and quality.

## **Conclusion**

This paper explores a new green engineering course that integrates economic and environmental sustainability concerns. The course utilized a group project to provide students with an experiential learning opportunity, while introducing students to life cycle assessment software, engineering economics, and triple bottom line decision analysis. The students generally performed well in the overall class and the group project (e.g., the majority of the class obtained a 70% grade or higher in the course). Future versions of this course could improve students' understanding of LCA software by introducing software earlier in the curriculum or including a laboratory component to the class. Lastly, this class provides skills that could be applied to a senior capstone course, which could enhance the student design experience in future semesters.

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