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From Code to Circularity: Infusing Sustainability into Civil Engineering Computer Programming Course

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Abstract

This paper examines the impact of incorporating project-based learning in a civil engineering programming course on students' perceptions of sustainability within the profession. A required sophomore-level course was redesigned in collaboration with Santa Clara University's Center for Sustainability to include a term-long project addressing a campus waste management challenge. The project aimed to connect programming and data analysis skills with a local, real-world problem while emphasizing sustainability as a core aspect of civil engineering practice.

The primary outcomes of interest from this study are perceptual and affective rather than performance-based, focusing on students' understanding of sustainability, empathy toward waste-related behaviors, and perceptions of the civil engineer's role in advancing sustainability and the circular economy. A mixed-methods approach was used, including pre- and post-project surveys and qualitative analysis of student reflections and project work. The study design did not include a control group.

Results indicate increases in students' perceived understanding of sustainability and recognition of the engineer's role in addressing societal challenges. Qualitative findings further suggest shifts toward more systems-level definitions of sustainability and increased personal accountability for waste practices. These findings suggest that embedding sustainability-focused, project-based experiences in technical courses can positively influence students' attitudes and sense of professional responsibility.

1. Introduction

The ASCE Civil Engineering Body of Knowledge (CEBOK) defines sustainability as "a set of environmental, economic, and social conditions—the triple bottom line—in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely, without degrading the quantity, quality, or the availability of natural, economic, and social resources" [1]. The CEBOK includes both cognitive and affective sustainability outcomes under the technical category suggesting that students should graduate with sustainability knowledge, skill and attitudes to be successful entry-level civil engineers [2]. ABET emphasizes sustainability through outcomes related to engineering design and professional responsibility, requiring students to consider environmental, societal, and economic factors in engineering decisions [3].

Civil engineering students have a favorable view and definition of sustainability but the definition is often limited and not fully integrated with engineering principles or professional responsibilities. In particular, many students define sustainability as an environmental issue, neglecting social and economic dimensions [4]. Prior research suggests these perceptions can broaden over time, with many students being able to define sustainability more broadly by their senior year [5,6]. Introducing professional competencies, including sustainability, early in the curriculum and continuing to practice the skills can help students retain the knowledge [6,7] and be prepared to apply non-technical aspects of sustainability to capstone design and entry into the profession [8].

Current curriculum interventions for introducing sustainability in engineering education primarily involve dedicated courses [9], and problem-based learning approaches [6]. Most sustainability interventions occur in design heavy-courses, or focus less on professional identity and more on environmental framing of sustainability. There is limited evidence on introducing sustainability in a technical but non-design course like computer programming, or how the course and content might change professional responsibility perceptions at the sophomore level.

This study addresses this gap by examining the impact of a sustainability-focused, project-based learning experience embedded within a required sophomore-level civil engineering programming course. Guided by the research questions: (a) How do students' perceptions of sustainability and professional responsibility change following the project? and (b) How do students describe the professional role of civil engineers in advancing sustainability after the project? This paper contributes evidence that embedding sustainability in a technical programming course can meaningfully influence students' sustainability understanding and perceptions of engineering capability, even in the absence of a traditional design context. A different paper [10] described how the project impacted students' technical skills.

2. Methods

One section of this course is offered annually and is a required course for sophomore civil engineering students at Santa Clara University, a midsize, primarily undergraduate private institution. The course introduces civil engineering students to computer programming through MATLAB with an emphasis on developing algorithms for complex problems. Data for this paper were collected during the Winter 2025 offering of the course.

The instructional intervention investigated in this paper is a project-based learning project in cooperation with the Center for Sustainability at Santa Clara University. The project required students to apply MATLAB to an open-ended, real-world sustainability problem with the Center for Sustainability acting as the client. The project emphasized both technical analysis and societal context. The main output of the project is a report to the Center for Sustainability that uses MATLAB to investigate an issue related to waste on campus. Details on the project and the collaboration with the Center for Sustainability are available in a previous paper [10]. The present study focuses specifically on students' perceptions of sustainability and professional responsibility, while the prior publication focused on how programming skills improved during the course. Relevant artifacts collected during the course of the project are presented in Table 1, with a full list of stages of the project and deliverables available in [10].

Table 1. Summary of activities and deliverables for the Service-Learning Project in Computer Methods for civil engineers

Activity	Description	Purpose	Data
1	Pre-project survey	Collect pre project survey results, including Likert responses and open-ended questions	Quantitative Qualitative
2	Reflection	Reflect on understanding of sustainability before and after the presentation from Center for Sustainability	Qualitative
3	Post-project survey	Collect post-project Likert response to survey questions	Quantitative

The pre- and post-course surveys were designed to measure students' changes in perceptions related to the relationship between civil engineering and sustainability and included the following statements which students ranked on a Likert scale from 1 (strongly disagree) to 5 (strongly agree):

- Waste and sustainability are related
- Civil engineers have the skills and knowledge to solve societal problems such as the circular economy and waste
- Civil engineers have a societal responsibility to solve societal problems such as the circular economy and waste

Survey items align with ABET student outcomes and the ASCE CEBOK outcome on sustainability. Table 2 presents the statements from the survey and ABET and CEBOK3 alignment. In this paper, intended learning dimension refers to the specific aspect of students' understanding or perception that each survey statement was designed to probe.

Table 2 . Alignment of survey statements with intended learning dimensions, ABET Student Outcomes, and ASCE Body of Knowledge (CEBOK3) outcomes

Survey Statement	**Intended Learning Dimension**	**ABET Student Outcome(s) [3]**	**ASCE Body of Knowledge (CEBOK3) Outcomes [2]**
Statement 4: *Waste and sustainability are related.*	Sustainability Understanding	**ABET 2** – an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	**Sustainability Cognitive Domain** - Ability to identify and explain concepts and principles of sustainability.
Statement 5: *Civil engineers have the skills and knowledge to solve societal problems such as the circular economy and waste.*	Engineering Capability	**ABET 2** – an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	**Sustainability Affective Domain** - Acknowledge the importance of sustainability in civil engineering.
Statement 6: *Civil engineers have a societal responsibility to solve societal problems such as the circular economy and waste.*	Professional Responsibility	**ABET 4** – an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.	**Sustainability Affective Domain** - Value the benefits of sustainability in the practice of civil engineering. Integrate a commitment to sustainability principles into the practice of civil engineering **Professional Responsibility Affective Domain -**Form judgments about professional responsibilities relevant to the practice of civil engineering including safety, legal issues, licensure, credentialing, and innovation.

The pre-project survey also asked students to define sustainability in their own words. The reflection in activity 2 asked students to reflect on how a presentation in class may have (a) changed how they define sustainability and (b) changed how they think about the connection between sustainability and their role as civil engineers. Responses from the open-ended questions and written reflections were used to contextualize and deepen interpretation of the quantitative findings.

Paired pre- and post-responses from the same students were compared using a Wilcoxon signed-rank test to identify statistically significant changes over time with significance assessed at $\alpha = 0.05$. Qualitative data was analyzed using thematic analysis. An initial coding scheme was developed for each set of questions by reviewing a subset of responses to identify recurring ideas. Responses were reviewed multiple times, iteratively refining the coding scheme and reapplying codes across the full dataset to ensure consistency. Responses to the sustainability definition question on the pre-project survey were compared with responses to part (a) of the reflection to examine how students' definitions of sustainability evolved over the course of the project. The second part of the reflection is used to understand if, after a sustainability related project, students recognize sustainability as part of the role of civil engineers.

3. Results

<u>Quantitative Survey Results</u>

Quantitative data comes from 41 students who completed both the pre- and post- survey and consented to their data being used in the study. Figure 1 presents mean pre- and post-survey responses for the three key statements identified in Table 2.

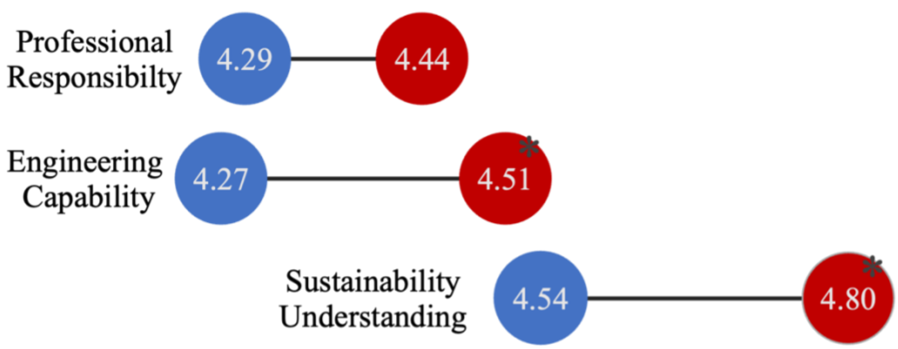

Figure 1. Mean pre- and post-project Likert responses for sustainability understanding, engineering capability and professional responsibility. Lines connect pre–post means and with blue circles representing pre-course data and red circles representing post-course data. Asterisks (*) denote a statistically significant change ($p < 0.05$*).*

Statistically significant increases were observed for students' understanding of the relationship between waste and sustainability ($p = 0.012$) and for perceptions of civil engineers' technical capacity to address societal challenges ($p = 0.025$). Although mean scores increased for students' perceptions of professional responsibility, this change was not statistically significant.

These results indicate that the course experience contributed to measurable gains in students' conceptual understanding of sustainability and confidence in engineering capability, while perceptions of professional responsibility remained relatively stable across the term.

Qualitative Data Results – Defining Sustainability

Qualitative analysis was conducted on students' free-response definitions of sustainability collected at the beginning of the course and on a post-course reflection prompt asking students to describe how their understanding of sustainability may have changed. Initial open coding of a subset of responses resulted in six thematic codes: longevity, environmental protection, resource conservation, future-thinking, systems-level sustainability practice, and cost. These codes were then applied to all pre-course definitions and post-course reflections. An additional code indicating no change in definition was included during analysis of the post-course reflections. Responses could be coded for multiple themes. Table 3 summarizes the frequency of each theme in pre- and post-course responses.

Table 3. Frequency of pre- and post- course themes from 41 students who completed all surveys.

Theme	Definition	Pre	Post
Longevity	Mentions durability, long-term use, or solutions that last over time.	20	3
Environmental Protection	Mentions of reducing harm to the environment, protecting ecosystems, or minimizing pollution.	35	10
Resource Conservation	Mentions efficient use of materials, minimizing waste, or conserving natural resources.	16	3
Future-thinking	Explicit consideration of future generations, long-term impacts, or forward-looking decision making.	7	3
Systems-level sustainability practice	Mentions multiple dimensions of sustainability including societal impacts and actions beyond environmental impact alone.	2	20
Cost	Mentions of affordability, economic efficiency, or financial considerations.	3	0
No Change	Explicit statements indicating the student's definition of sustainability did not change.	NA	20

Analysis of pre-course responses indicated that students most commonly defined sustainability in terms of environmental protection, longevity, and resource conservation. These definitions emphasized minimizing environmental impact or designing solutions that last a long time. At the beginning of the project only two students defined sustainability at a systems level. Post-course responses showed a substantial increase in the number of students acknowledging a systems-level approach to sustainability.

Because the post-course prompt asked students to describe changes in their thinking, the reduced frequency of environmentally focused themes should be interpreted as an expansion of students' definitions rather than a shift away from their original understanding. For example, one student initially defined sustainably saying "*Something being sustainable means that it is working to limit its environmental impact while also being long-lasting and effective.*" And then reflected after learning more, "*At the beginning of the presentation, I felt familiar with the slides of the UN goals, but I liked seeing the people, planet, and profit slide. Previously, I never thought about the environment encompassing our society and our economy.*" This shows the students growth in the definition to include systems thinking and the multiple dimensions of sustainability.

Qualitative Data Results – Sustainability & Civil Engineering Profession

Initial coding for the reflection question that asked students to articulate the connection between sustainability and civil engineering identified four main themes: professional responsibility, design decision making, systems and infrastructure, and constraints. An additional code was added for responses that showed a limited or uncertain relationship in the responses. The difference between design and constraints is responses coded for design included those where students mention parts of the design process and in particular mention the design of environment related projects including river restoration or waste management. On the other hand, responses that were assigned the code of constraints discussed using sustainability as a design constraint for a wide range of projects, most notably structures and construction. Table 4 shows the counts for each of the themes.

Table 4. Number of responses (out of 41) that indicated each of the four main themes, plus responses

Theme	Professional Responsibility	Design	Systems and Infrastructure	Constraints	Limited/ Uncertain
Count	19	8	12	14	16

The most prevalent theme in students' responses was professional responsibility. After the start of the project, many students described sustainability as an obligation of civil engineers and include broad societal and environmental considerations. As one student explained, *"As civil engineers, our role extends beyond designing buildings and roads—we are responsible for creating efficient and sustainable infrastructure."* Another student articulated this responsibility in ethical terms, noting that because civil engineering projects endure for decades, *"Beyond technical skills, I've realized the ethical needs of sustainability. Civil engineers design and contribute to infrastructure that lasts decades, and our choices lock in environmental impacts."*

Students also frequently frame sustainability as a design constraint. These students discussed sustainability as a factor that limits and guides design decisions. For example, one student wrote, *"One way to achieve this is by designing structures that use the least amount of material necessary while still being structurally sound. This approach minimizes waste production and allows resources to be used elsewhere."* These responses emphasize sustainability as something that must be considered during the engineering design process.

Fewer students extended this discussion to systems or infrastructure-scale impacts, explicitly describing sustainability within larger engineered systems such as transportation networks, water infrastructure, or the construction industry as a whole. A subset of students' responses was not clear in the relationship between sustainability and their role as a civil engineer, indicating that professional identity related to sustainability remains under development.

4. Discussion

The biggest takeaway in this study is that sustainability interventions embedded in a technical, non-design course can meaningfully impact students' definitions and understanding of sustainability. Both the quantitative and qualitative findings suggest students expanded their definition of sustainability beyond environmental considerations to include systems-level thinking that integrates environmental, social, and economic dimensions. This expanded definition aligns with the two lowest levels of the CEBOK cognitive domain for sustainability, and demonstrates that these learning outcomes can be achieved without a full course redesign, instead it was through a redesigned project.

The project served as a connection between technical and non-technical learning objectives. Students who entered the course with strong programming skills were required to apply those skills within a broader context, while students initially less confident in programming were able to engage through a project that emphasized sustainability and impact. This suggests that sustainability-focused projects may function as an inclusive pedagogical strategy in technical courses, supporting engagement across a range of students.

Although changes in students' perceptions of professional responsibility were not statistically significant over the duration of the project, qualitative findings indicate that many students began to describe sustainability as a professional obligation of civil engineers. Given that participants were sophomore students, additional growth in this area is expected during the final two and a half years of education. Prior work suggests that professional responsibility emerges gradually through repeated exposure and reinforcement [6,7] and in this context, the project may represent an early affective intervention that lays groundwork for later growth. Because the project structure centers on locally relevant datasets and broadly applicable analytical skills, this approach can be implemented across institutions and technical courses without requiring major curricular restructuring.

5. Limitations and Future Work

This study has several limitations that should be considered when interpreting the findings. First, there was no control group. The project was implemented in the only available section of the course, The study also relied on self-reported data and reflection rather than performance-based assessments of skills, which introduces potential bias. The course and the curricular intervention were only completed at one institution so the results are limited to same or similar institutions.

Future work could incorporate performance-based measures, such as rubric-based evaluation of sustainability considerations in technical analyses, to complement self-reported perceptions. In addition, continued tracking of students understating of both the cognitive and affective domains of CEBOK definitions as well as ABET outcomes will give a longitudinal view of the data. Additionally, applying the intervention to other institutions, both similar and different would be helpful.

6. Conclusion

A project partnered with the University's Center for Sustainability was introduced into a required sophomore level computer programming for civil engineers course with the goal of increasing interest in computer programming skills, and teaching students about sustainability and its importance for the civil engineering profession. The data showed that understanding and application of an expanded definition of sustainability increased, and that professional responsibility related to sustainability in civil engineering showed qualitative importance. This suggests that sustainability does not need to wait for a full course or upper division design experience to be meaningful for civil engineering students, and that professional responsibility can be shaped within technical courses.

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