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Sustainability Components Assessment of Engineering Design Capstone Projects

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Dr. Bilal Alhawamdeh, a Ph.D. in Civil Engineering from Western Michigan University, is a distinguished Senior Research Associate with a keen interest in integrating sustainablity in engineering education. His career is marked by the development of innovative educational programs and curricula, emphasizing the integration of sustainability into engineering studies. Dr. Alhawamdeh is a proponent of smart technology in classrooms and has supervised numerous senior capstone and student research projects focused on sustainable solutions. His work also involves fostering collaborations between industry and academia, enhancing the practical impact of engineering education.

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Abstract

As the engineering community grapples with integrating sustainability into its curricula, assessing how sustainability concepts are infused across various engineering disciplines remains challenging. The senior design capstone project is pivotal in assessing students' understanding of engineering subjects. Thus, it acts as an effective measure of their awareness and proficiency in sustainability. This study assesses the integration of sustainability in senior design capstone projects across six engineering programs, namely, Chemical and Paper Engineering, Civil and Construction Engineering, Electrical and Computer Engineering, Engineering Design Manufacturing and Management Systems, Industrial and Entrepreneurial Engineering and Engineering Management, and Mechanical and Aerospace Engineering, utilizing a validated sustainability rubric. The assessment focuses on seven critical criteria: dimensions, cognitive levels, links, drivers, integrations, qualitative and quantitative incorporation, and sustainability topics. The assessment was conducted using an interrater reliability approach between two researchers. One key revelation from the study is that sustainability is more integrated within the projects' fabric than existing as a stand-alone element. This integration, however, is significantly influenced by instructor-driven expectations. The analysis across the six programs indicates that if sustainability is not highlighted as a primary project deliverable, students are less inclined to incorporate sustainability concepts acquired from previous coursework into their reports. This finding underscores the importance of explicitly embedding sustainability requirements within project guidelines. The study advocates incorporating sustainability experts directly into senior design courses, acting as course advisors or project mentors, to strengthen the emphasis on sustainability. This initiative has shown promising results in specific projects across the

examined programs, potentially setting a precedent for a more embedded and holistic approach to sustainability in engineering education.

1. Introduction

The integration of sustainability in engineering education has been a subject of interest among engineering educators for many years. This concept involves embedding sustainability-related components into engineering curricula, which can be understood through two primary contexts: macro and micro. In the macro context, there is an emphasis on empirical models for curriculum integration. For instance, Arsat et al. (2017) highlight the challenges of introducing stand-alone sustainability courses, opting for student-centered learning to integrate sustainability into engineering curricula[1]. This approach allows for incorporating sustainability without compromising the technical and engineering content. Similarly, Thürer et al. (2017) conducted a systematic review emphasizing the need to integrate sustainability into engineering curricula, highlighting various methodologies and future research questions[2].

In the micro context, the focus shifts to learning strategies that enhance students' awareness and skills towards sustainability. Guerra (2017) discusses the role of problem-based learning (PBL) in integrating sustainability into engineering education, highlighting its potential to address the challenges of sustainability integration[3].

Assessment of sustainability competencies remains a concern. Researchers like Ashraf and Alanezi (2020) explore incorporating sustainability concepts into engineering curricula, suggesting approaches like a micro-curriculum and stand-alone courses[4]. Moreover, tools such as the Sustainability in Higher Education Assessment Rubric (SHEAR) and Sustainability Assessment Survey (SAS) have been empirically validated and proposed for assessing sustainability competencies in higher education.

Dancz et al.[5] developed a new instrument to assess senior design projects in engineering, addressing the shortcomings of previous tools in capturing multi-disciplinary knowledge transfer, particularly in sustainability. While their study was limited to Civil Engineering departments, exposing a gap in a broader application, this study extends the use of their instrument to various engineering departments, aiming to comprehensively evaluate student mastery in senior design projects across the field.

2. Method

This study evaluated the integration of sustainability concepts in senior design capstone projects across six engineering programs at a higher-research U.S. institution during the 2022/2023 academic year. Ninety-eight senior design projects were assessed for their application and inclusion of sustainability concepts (see Table 1). The programs encompassed various engineering programs, offering a comprehensive view of sustainability education in engineering curricula. The method employed for this assessment followed the framework established by Dancz et al.[5] (2017) in their study of engineering curriculum and sustainability education. This approach was chosen due to its proven efficacy in examining the cognitive extent to which sustainability concepts are integrated into engineering projects.

The rubric used for assessment was developed by Dancz et al.[5] (2017) and consists of specific criteria designed to measure the depth of sustainability integration in engineering projects. Table 2 presents the rubric criteria in detail for clarity and reproducibility. This rubric allowed

for a standardized evaluation of the senior design projects, ensuring consistency and reliability in the assessment process. Each project was independently assessed by two researchers using the rubric. The researchers evaluated the extent of the integration of sustainability concepts, considering factors such as the application of sustainable design principles, consideration of environmental impacts, and the inclusion of sustainable practices in the project execution. Inter-rater agreement was calculated between the two researchers to ensure the validity of the assessment. Discrepancies in evaluations were discussed and reconciled to reach a consensus. This process not only strengthened the reliability of the assessment but also allowed for a comprehensive understanding of the rubric application.
The results of the rubric evaluation were then collated and analyzed to identify trends, strengths, and areas for improvement in sustainability education within the engineering programs. This analysis provided insights into how effectively sustainability concepts are being integrated into the engineering curriculum and highlighted opportunities for enhancement in future educational strategies.

Table 1: Engineering programs, their indices, and corresponding senior design projects' number

Engineering program	**Index**	**Projects' number**
Civil and Construction Engineering	CE	10
Chemical and Paper Engineering	ChE	13
Computer Engineering and Electrical	CEE	14
Engineering Design, Manufacturing and Management Systems	DME	13
Industrial and Entrepreneurial Engineering and Engineering Management	IM	7
Mechanical And Aerospace Engineering	MAE	41

Table 2: Sustainability rubric developed to assess student application of concepts[5]

Criteria		Possible Score
1. Dimensions of Sustainability	Environmental Economic Social	No Evidence, Weak, Fair, Good
2. Cognitive levels of sustainability topics incorporated		1. Knowledge (recall of information) 2. Comprehension (demonstrating, discussing) 3. Application (applying knowledge, designing, experimenting) 4. Analysis (recognizing trends and patterns) 5. Synthesis (using old concepts to create new ideas) 6. Evaluation (assessing theories and outcomes)
3. Sustainability Links	No Evidence	
	Concepts	Societal Economic Environmental
	Crosslinks	Societal-Economic Economic-Environmental Environmental-Societal
	Interdependent	Societal-Economic-Environmental
4. Was sustainability in the project client-driven, student-driven or other?		Student Client Other Rubric / Instructor
5. Was sustainability integrated throughout the report or stand-alone section of the report?		Sustainability was integrated throughout sections Sustainability was stand-alone section in report
6. Quantitative or qualitative incorporation of sustainability?	Environmental Economic Social	Quantitative Qualitative
7. Source/ reference cited for sustainability concept		Yes No
8. Sustain-ability Topics (explicit/ implicit)	Sustainable Agriculture, Sustainable Land Use, Industrial Ecology, Corporate Sustainability, Climate Change, Renewable Energy, Green Buildings, Sustainability Infrastructure, Green Construction, LCA (Life Cycle Assessment), Material Flow Analysis, Natural Resource Depletion (or Scarcity), Pollution Prevention, Design for the Environment, Green Chemistry, Environmental Justice, Embedded/Virtual Water Use, Anthropogenic Environmental Impacts, Sustainability Rating Schemes (e.g., LEED), Resilience, Urbanization/urban sprawl, Sustainability economics, Governance for sustainability, Sustainable Innovation, Sustainability Ethics, Other 1- recycling, Other 2- water reuse, Other 3- energy reduction, Other 4- Urban heat island effect, Other 5- alternative transportation, Other 6- consider needs of people/ stakeholder engagement, None	

3. Discussion

The assessment outcomes of senior design capstone projects are analyzed and discussed in this section to evaluate students' sustainability education level of integration by focusing on the understanding of sustainability topics, the extent of cognitive application of sustainability, the depth at which students apply sustainability concepts, and their proficiency in using both quantitative and qualitative approaches for sustainability.

Figure 1 showcases the contrary to the typical trend in sustainability where environmental factors often lead. In these senior design projects, the Economic dimension dominates. A substantial number of projects have 'Good' incorporating economic sustainability, which could reflect a curriculum or project objectives that heavily emphasize cost-effectiveness, financial viability, and possibly the market impacts of the designs. While not as prominent as the economic, environmental sustainability still shows a significant presence, especially in the 'Good' and 'Fair' categories. This indicates that environmental considerations are taken seriously, aligning with global concerns about ecological impact, though they are seemingly secondary to economic factors. Social sustainability is notably less represented, especially in terms of 'Good' integration. The prominence of 'No evidence' in this category suggests that social aspects, such as community impact, user inclusivity, and social equity, are less frequently addressed or perhaps more challenging for students to articulate and incorporate into their projects.
The trend here indicates a strong focus on the economic impact of design projects, a moderate but notable consideration of environmental factors, and a need for greater emphasis on social sustainability. This pattern might reflect the priorities of the industries students are preparing to enter, or it could result from the metrics and guidelines provided to them for project development. It points to an opportunity for academia to balance the sustainability triad by strengthening the integration of social aspects into the engineering curriculum and project evaluation criteria.

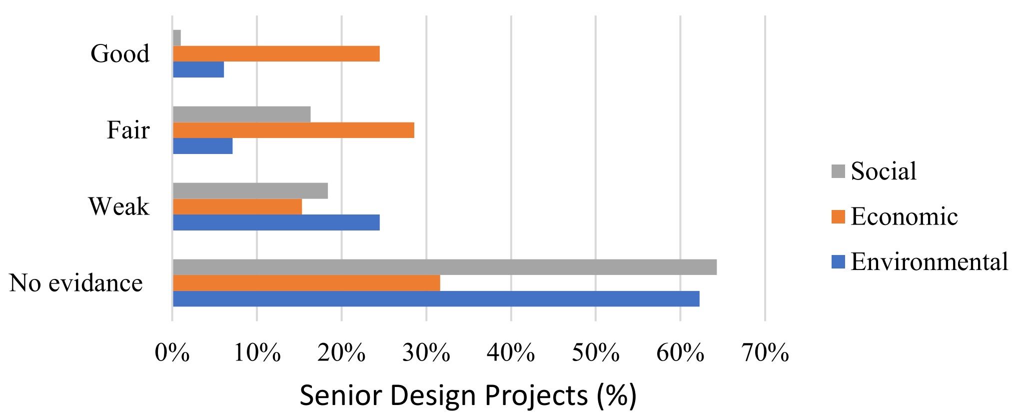

Figure 1: Dimensions of sustainability present in senior design projects.

Figure 2 shows that the IM program is the best example of senior design projects integrating three sustainability dimensions among other departments. The result, however, did not precisely correspond with how students integrated sustainability concepts into their senior design projects.

Figure 3 illustrates that senior design projects from IM only demonstrated qualitative evidence in environmental and social elements and scored well when quantifying sustainable components in economic aspects.

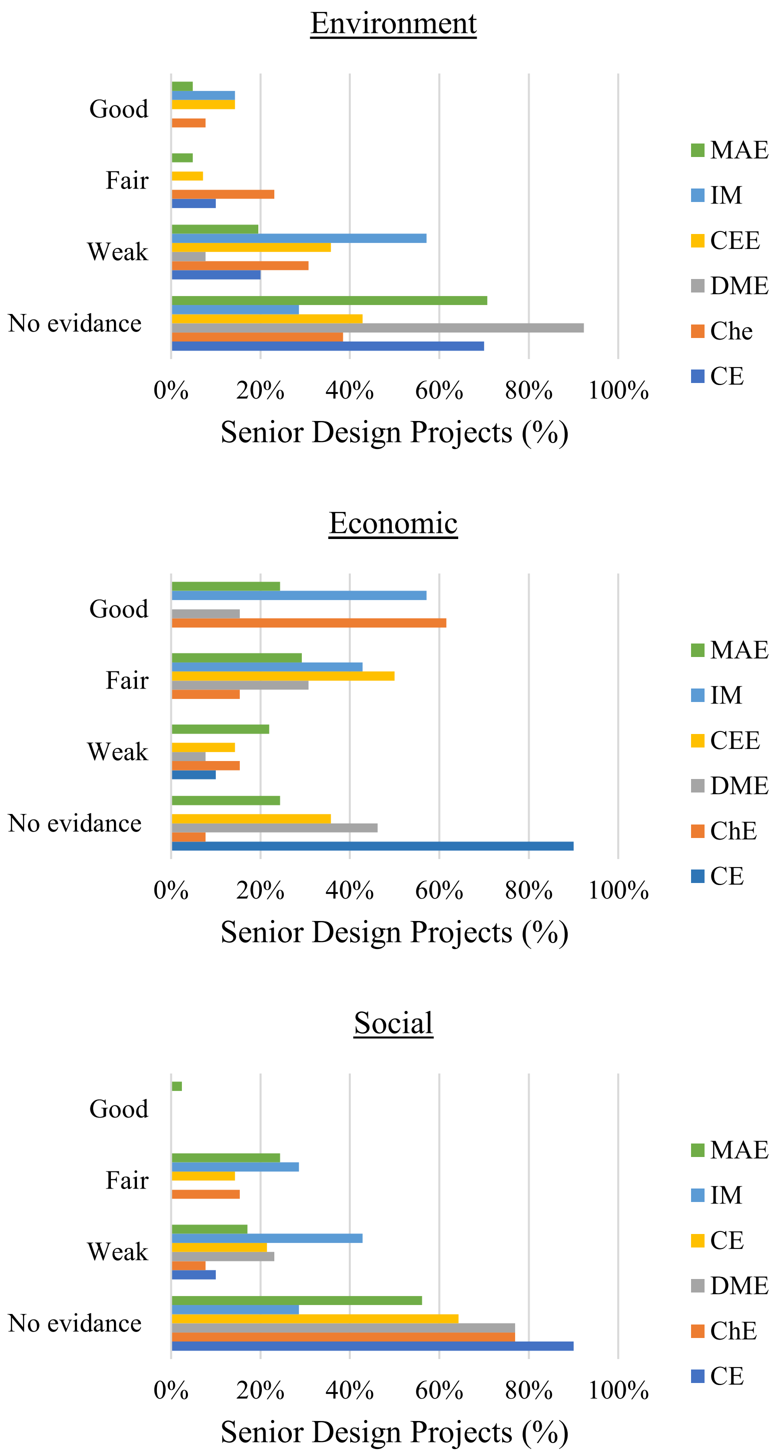

Figure 2: Dimensions of sustainability present in senior design projects per program.

On the other hand, senior design projects from ChE could provide sufficient quantitative proof in both the economic and environmental domains despite their slightly lower performance than IM. This pattern is consistent with the cognitive level of sustainability components demonstrated in the senior design projects assessed. In this case, senior design projects from ChE are the most excellent examples of presenting sustainability components up to the analysis, synthesis, and evaluation level, as indicated in Figure 4. The discrepancy pattern observed might be attributed to the various characteristics and the depth and breadth of sustainability components highlighted by different professors in each department. The most intriguing finding is that CE is the only department explicitly addressing sustainability in senior design project descriptions. However, this department does not appear well in any sustainability domain.

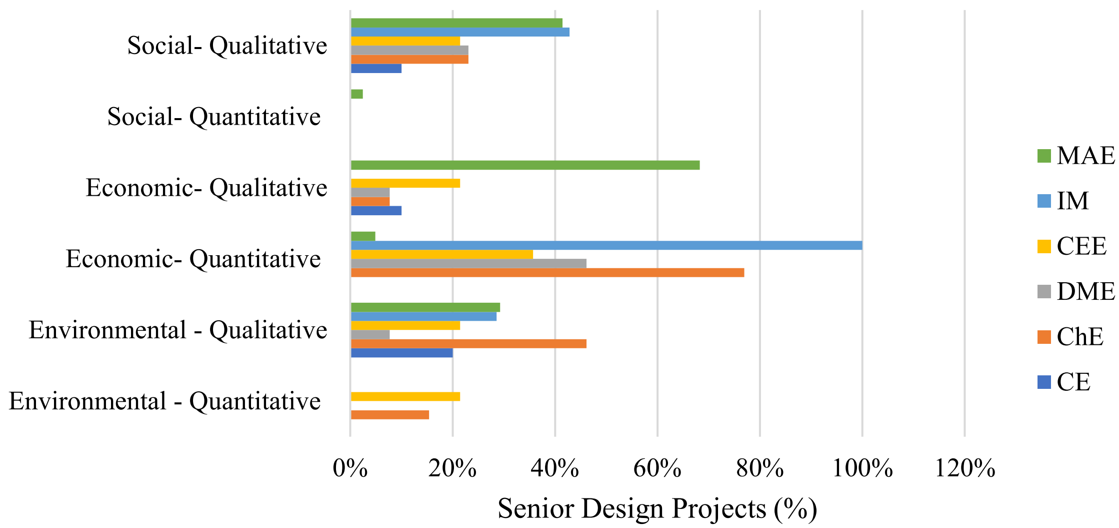

Figure 3: Quantitative/qualitative incorporation of sustainability in senior design.

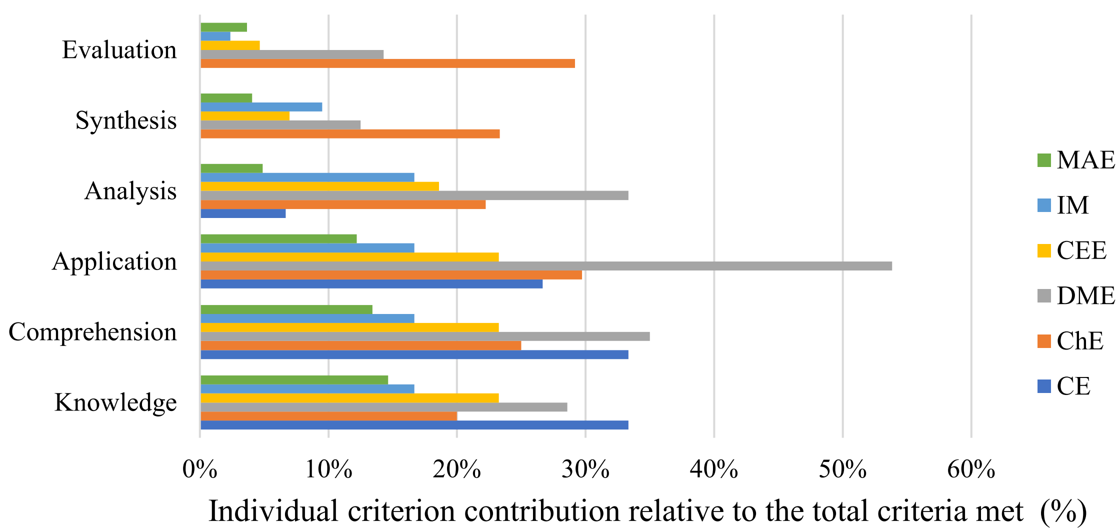

Figure 4: Bloom's taxonomy achieved in senior design projects per engineering program.

Figure 5 shows insights into senior design projects revealing a traditional inclination towards cost reduction as the driving force behind engineering solutions, with 'Sustainability Economics' being the most frequently addressed sustainability topic. This trend, evidenced by its representation in roughly 47.5% of the projects, underscores a conventional emphasis on economic factors in engineering design, often taking precedence over other sustainability dimensions. While cost-effectiveness is undeniably crucial in engineering, the relatively lower representation of 'Energy Reduction' and 'Renewable Energy' topics, at approximately 13% and 12%, suggests that environmental and social aspects of sustainability receive less focus. This disparity highlights an adherence to the typical priority of minimizing costs, possibly at the expense of optimizing environmental and social outcomes.

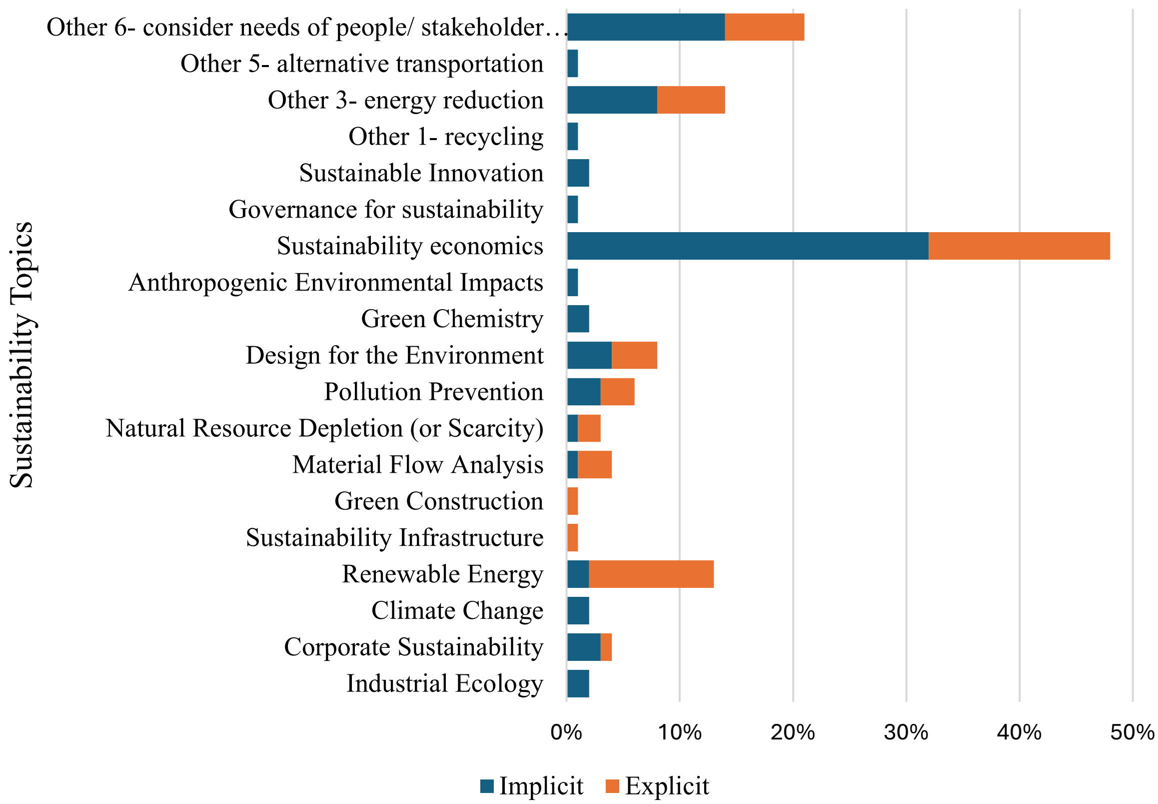

Figure 5: Sustainability topics present in senior design projects

Figure 6 highlights the integration economic, environmental, and social factors in engineering capstone projects. Economic factors, occupying 53.1% of the diagram, predominantly influence engineering decisions, emphasizing cost and profitability. However, the 10.2% overlap between economic and environmental factors and the 9.2% overlap with social factors indicate a shift towards valuing environmental and social impacts more in these projects. While economic aspects are still paramount, the 13.3% for environmental and 17.3% for social dimensions reflect their growing integration in project analysis. The diagram's overlapping regions reveal an increasing focus on balancing cost, sustainability, and societal impact in engineering education, suggesting a move toward a holistic project evaluation. However, the relatively smaller overlaps, compared to those in the economic dimension alone, suggest that educational programs should emphasize integrating all three factors to better prepare students for modern engineering challenges. For example, the philosophy of capstone design projects within the engineering programs is pivotal in assessing eight out of eleven Accreditation Board for Engineering and Technology (ABET)[6] outcomes. However, there is a lack of explicit emphasis on incorporating sustainability impact in engineering solutions.

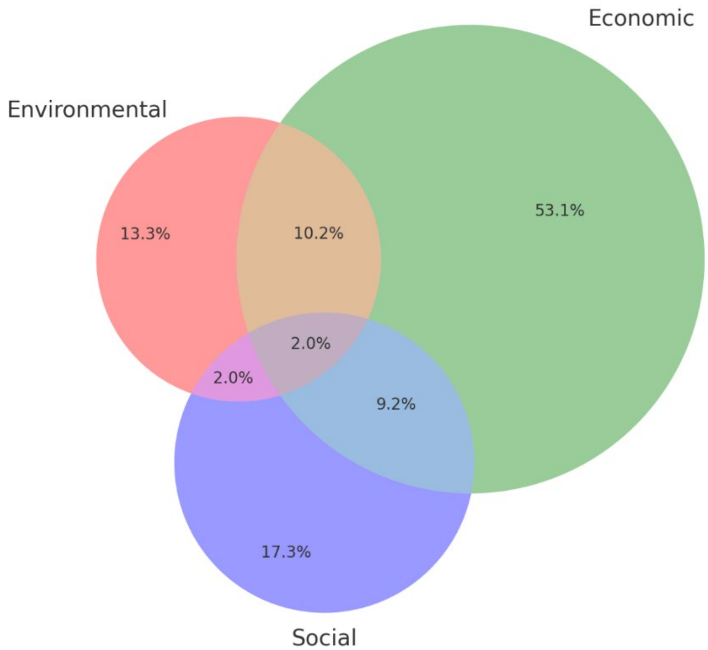

Figure 5: Venn diagram for sustainability link within the capstone research projects.

4. Conclusion

This comprehensive assessment of sustainability integration in senior design capstone projects across various engineering disciplines at U.S. University has illuminated several key insights and challenges in sustainability education within engineering curricula. While using the sustainability rubric developed by Dancz et al.[5] (2017) has provided a valuable framework for evaluating nighty-eight projects, the findings reveal significant areas for improvement and further research.

A primary observation is the predominant focus on the economic dimension of sustainability, often at the expense of environmental and social considerations. This trend reflects a curriculum bias towards cost-effectiveness and financial viability, suggesting the need for a more balanced approach to sustainability education that equally emphasizes all dimensions of sustainability. Despite identifying sustainability components in many senior projects, there are notable challenges in the depth and quality of sustainability integration. Most projects lacked physical evidence of sustainability components, and many discussed qualitative aspects without quantitative analysis, making it challenging to measure students' competencies accurately. Furthermore, the projects often addressed only specific dimensions of sustainability, indicating a partial comprehension of sustainability competencies. A concerning finding is that most projects only achieved lower-order thinking skills based on Bloom's taxonomy, revealing that students may not have acquired the expected level of sustainability competencies from their courses.

This study suggests that a sustainability assessment relying solely on senior design projects is insufficient. Future research should explore designing independent tests specifically devoted to assessing sustainability competencies in engineering departments. Additionally, integrating sustainability-related items into assessments administered in sustainability-related courses could provide a more comprehensive evaluation of students' understanding and application of these concepts. Moreover, an in-depth analysis of teaching materials and classroom observation in qualitative settings could significantly contribute to future studies. This approach would offer insights into integrating sustainability competencies within specific courses, thus enhancing the overall effectiveness of sustainability education in engineering programs.

In conclusion, while there are promising indications of sustainability integration in engineering education, there is a clear need for more structured, consistent, and comprehensive approaches. Strengthening the integration of all sustainability dimensions and enhancing the depth of cognitive application in student projects are essential steps toward preparing future engineers for the multifaceted challenges of sustainable development. The findings from this study serve as a call to action for academia to lead in embedding sustainability more effectively and holistically in engineering curricula.

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