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Redesigning a Chemical Engineering Capstone Course: Integrating Sustainability, Social Responsibility, and Entrepreneurial Mindset

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1. Introduction

Our society has become increasingly aware of the environmental, public health, and socio-economic impacts driven by industrial processes. Promoting sustainable development is critical for maintaining societal well-being. Research underscores the necessity for engineers to understand social, global, and cultural dimensions as they transition into the workforce[1], [2], [3].

Engineers are uniquely positioned to research and develop solutions to global challenges. Integrating socio-cultural perspectives into their approach fosters more inclusive and equitable designs. This paper presents the redesign of a Chemical Engineering Senior Design Capstone course aimed at embedding sustainability and social responsibility in engineering practices. The course emphasizes core engineering design principles alongside an entrepreneurial mindset, with a specific focus on projects centered around sustainable technologies and markets. It further introduces students to critical aspects of social responsibility by addressing global and environmental issues, diversity, equity, and inclusion (DEI) considerations, and the necessity of sustainable technological innovations within chemical engineering.

The paper delves into key aspects such as how students engage in decision-making concerning social and environmental challenges in specific geographical contexts, how they integrate DEI into company practices and teamwork dynamics, and how they assess the necessity and implications of sustainable technologies. The analysis also evaluates the redesign's impact on student self-efficacy, learning outcomes, and the quality of their projects.

2. Background

There has been an increased focus to address sustainability and social impacts in engineering education. So much as that ABET has updated its 2022-2023 Student Outcome 2 to reflect this by emphasizing "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" [4]. Also, ASEE has launched the Engineering for One Planet (EOP) framework that helps guides educators to implement sustainability focused topics into their curriculum[5]. Specifically in chemical engineering education, the integration of sustainability and social responsibility is increasingly recognized as essential for preparing future engineers to address complex global challenges.

Studies demonstrate that problem-based learning approaches foster a deeper understanding of sustainability concepts by encouraging critical thinking and real-world problem solving [6]. This sentiment is echoed by Allen et al., who note that over the past 25 years, there has been a marked increase in the inclusion of sustainability and green engineering principles in chemical engineering curricula, although challenges remain in fully integrating these concepts into core courses [7].

Addressing social responsibility through curriculum redesign complements sustainability efforts by broadening student awareness of societal impacts. Saienko emphasizes that engineering education must transcend technical knowledge to include social and economic considerations, thereby fostering a generation of engineers equipped to engage with socially responsible design [8]. One way chemical engineering curriculums address social responsibility is through process safety courses which address risk management, chemical hazards, and policies such as OSHA. However, they often lack a comprehensive exploration of broader socio-environmental, economic and cultural contexts of social responsibility that sustainability would address.

Though sustainability has been shown to be needed to incorporate into the Chemical engineering curriculum, little has been shown to be added to the capstone courses. One paper by Chen et. al. discussed incorporating sustainability into three different Chemical Engineering courses: Capstone, Green chemistry, and Material and Energy Balances[9]. It outlined how sustainability can be incorporated into these courses but did not give full details on how it could be implemented. Furthermore, the incorporation of interdisciplinary projects, as noted by Bacon et al., can enhance student engagement and understanding of sustainability issues by connecting engineering with social and ecological sciences [10].

Interdisciplinary projects that connect engineering solutions to social and ecological sciences have been found to enhance student engagement and understanding. For example, collaborative efforts across different disciplines allow students to develop holistic solutions that consider economic, cultural, and environmental factors. Such approaches highlight the necessity of ongoing curriculum adaptation to meet the ever-changing demands of industry and society. Capstone design course allows for the perfect outlet for students to apply their chemical engineering knowledge to the evolving landscape of chemical engineering applications in society and necessitates a commitment to fostering a culture of sustainability and social responsibility that prepares graduates for the complexities of modern engineering challenges.

3. Course Structure and Implementation

The Capstone process design course at Northeastern University is a one semester, 4 credit hour, project-based course where teams design a chemical process for a product or system with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors. All projects require applications of chemical engineering curriculum such as material and energy balances, kinetics, thermodynamics, and mass and heat transport and using the engineering design process to come up with a business plan, consider multiple designs, and come up with a final detailed design process. The design is validated with proof of concept data from a prototype, experiments, or simulation of the process to show the design is feasible and use that data to improve the design. Teams present, in multiple formats, the progress and final design to peers and the greater chemical engineering community and also submit multiple progress reports that turn into the final design report at the end of the semester.

Project topics are specifically selected to address real-world sustainability and environmental issues that have valuable positive societal impacts. The decision to redesign the capstone course was motivated by the need to enhance student engagement with sustainability principles and social responsibility, preparing them for careers that increasingly demand consideration of these factors. The redesign also aimed to foster an entrepreneurial mindset by encouraging students to identify market-driven solutions to societal challenges.

3.1 Core Design Principles

The course followed a structured engineering design process that required teams to conceptualize, design, and test innovative processes addressing societal needs. Students engaged in iterative design thinking, which allowed them to refine their ideas based on feedback and new insights.

3.2 Project Selection

Projects were sourced from alumni, faculty, and industry partners, ensuring that they addressed real-world sustainability challenges. Projects were chosen to emphasize life cycle analysis, environmental impact assessments, and the sourcing of sustainable materials. This approach allowed students to evaluate the trade-offs between different design options and make informed decisions that prioritized sustainability.

3.3 Project Milestones

There are 4 large milestones throughout the semester that guide the students to scope, define, analyze design decisions, implement, and collect data to determine project feasibility, both technically and economically.

3.3.1 Feasibility Memo

The feasibility memo lays the groundwork for the project by identifying the problem to be addressed, explaining its global or environmental importance, proposing initial ideas for solutions, and highlighting the significance of resolving the issue. It emphasizes understanding the core challenges related to the project and requires teams to consider how their design goals and decisions will account for public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors. To define the project scope, teams must conduct thorough research to assess the current impact of the problem and make informed decisions about addressing these issues. This memo serves as a crucial first step in clearly defining the problem and developing effective design solutions.

3.3.2 Business Plan and Base Case Design

The business plan report serves as a foundational document, providing essential background on the project's problem and the scientific principles behind the proposed process. It includes a mission statement and a Diversity, Equity, and Inclusion (DEI) statement. As part of the business plan, teams conduct a market analysis to identify the needs and costs associated with the product or process. This analysis examines current producers, existing alternatives, production volumes, pricing, and market demand. Additionally, it highlights what differentiates the team's design or product from what is currently available. Teams are also tasked with developing Base Case Designs, which outline specific design goals and criteria, prioritize these goals, and explore multiple design options using block flow diagrams (BFDs) and process flow diagrams (PFDs). A unique aspect of this course is its emphasis on sustainability, a topic often underrepresented in traditional capstone courses. Teams must evaluate sustainable design criteria, including the sources and life cycle of raw materials, energy, water, and resource requirements, as well as considerations for the end-of-use phase of the product or process. This includes examining product use, energy and resource demands, shelf life, by-products, waste management, and strategies for minimizing environmental and social impacts.

By integrating these sustainability considerations into their process designs, students develop a deeper understanding of how sustainability can be effectively implemented. They assess the impact of their design goals and incorporate these insights to refine and execute their final designs.

3.3.3 Detailed Design

The detailed design phase provides a comprehensive explanation and justification of the proposed process. It includes a complete Process Flow Diagram (PFD) that incorporates heat integration, stream flows, and compositions, as well as detailed specifications for process conditions and the sizing of each unit operation. A critical aspect of this phase is ensuring compliance with safety, health, and environmental codes and regulations. This involves the development of a Piping and Instrumentation Diagram (P&ID), a Safety Data Sheet (SDS) summary, and a Hazard and Operability (HAZOP) analysis. Additionally, proof-of-concept testing is conducted using simulated or experimental data to validate, refine, or reconsider design choices. This data is used to assess the design’s sustainability impacts, including energy consumption, water use, carbon emissions, and waste generation. Based on these evaluations, the designs are adjusted to reduce their environmental and societal impacts, ensuring a more sustainable outcome.

3.3.4 Final Design Report

The final report brings together the business plan, base case design, and detailed design into a comprehensive document, incorporating an economic analysis of the process. This stage integrates the technical and business aspects of the project to evaluate whether it is economically viable for production and market sale. The report also revisits and assesses the environmental, societal, and economic design goals established during the feasibility memo stage. These evaluations ensure that the project aligns with the broader objectives of sustainability and societal impact, providing a well-rounded assessment of the design's feasibility and effectiveness.

This structured approach for the capstone process design course not only ensures technical rigor but also emphasizes sustainability, societal impact, and economic viability, preparing students for real-world challenges in design and engineering.

3.4 Integrating Sustainability, Social Responsibility, and Entrepreneurial Mindset

Social responsibility and DEI considerations were embedded into the course in a variety of ways. Instruction included discussions on diversity, equity, and inclusion in both team practices and company strategies. Students were encouraged to reflect on the social implications of their designs and consider how their projects could promote equity and inclusion. Teams developed charters that outlined inclusive practices to ensure equitable participation. Inclusive team practices were implemented, as outlined in the paper by Pfluger et.al.[11] After each milestone, students evaluate themselves and teammates using a five-point behavioral scale on five criteria: (a) contributing to the team; (b) interacting with teammates; (c) keeping the team on track; (d) expecting quality from the team; and (e) having relevant knowledge, skills, and abilities to foster communication and more effective team practices.

Entrepreneurial mindset and sustainable market focus was implemented by students developing comprehensive business plans for their sustainable processes. These plans included market analyses to identify societal needs, competitive advantages, and strategies for sustainable scaling. By integrating entrepreneurial elements, the course prepared students to think beyond technical solutions and consider the broader market and societal impacts of their innovations.
Socio-environmental context in project work was added in a few ways. Instruction included lectures on sustainability, life cycle analysis, and trade-offs in material selection. Students were tasked with weighing the environmental costs of raw materials against their benefits and considering the long-term sustainability of their chosen solutions. Students assessed local and regional socio-environmental challenges relevant to their projects.

3.5 Project Examples

Here are a few examples of projects performed by the students. These are abstracts written by the students on the project premise and outcomes.

Example 1: Design of a Thermal Storage solution for Vertical Farm for an Indigenous community in Northern Canada

This project aims to design and optimize a thermal storage solution for a vertical farm that is sustainable and environmentally friendly. The capstone team consulted for AgriTech North, a non-profit organization based in Dryden, ON, with a mission to battle the larger issue of food insecurity that plagues indigenous communities in Northern Ontario. The current facility operates on electricity and natural gas, both of which require grid access. The new proposed vertical farm will use hybrid solar-thermal panels to capture electricity and waste heat, distributing heat to an Enersion chiller and a thermal storage system. Then, heat in the thermal storage system will be distributed throughout the facility. Typical thermal storage techniques and heat transfer fluids are not plausible design solutions due to the severely cold climate in the area. The proposed design utilizes a potassium formate-based heat transfer fluid (HTF), which has a reliable operating range down to -55°C, is biodegradable and safe for the environment, and has a reasonable price. The proposed thermal storage system is a well-insulated tank containing hexadecane wax to store latent heat. Simulation of the process in Python serves as proof of concept, and is used for calculations, equipment sizing, and evaluation of design choices. Included in the simulation are heat transfer equations accounting for insulated tank sizing, heat collection at the solar panels, heat loss from conduction to the outside air, heat load generated by the lights in the grow rooms, and diversion of heat out of the grow rooms through the gas-liquid heat exchanger. Using this simulation, the facility's current heat load/energy usage, and the local solar irradiance data, a thermal storage system was designed and optimized. Based on the simulation, a 2,500-gallon hexadecane wax thermal tank is proposed to store the daily energy generated by 120 photovoltaic solar panels and 30 solar thermal panels. The system will require supplemental energy to meet demand on cloudy days based on available weather data, so the use of a boiler is proposed to meet the remaining demand. 6,509.36 m3 of natural gas are projected to be required compared to the current electrical demand of 234,511.20 kWh. The projected cost of the thermal solution is $459,831.04, which is below the total system budget of $600,000. The thermal solution is expected to reduce operational costs by $35,279.25 per year which equates to a payback time of 13 years.

Example 2: PFAS destruction in Southern Maine Regional Biosolids Processing Facility.
In 2022, Maine banned the land application of sludge, the biosolids product of wastewater treatment, because of concerns over per- and poly-fluoroalkyl substances (PFAS) contamination. As a result, wastewater treatment facilities (WWTFs) around Maine dispose of all sludge in landfills. However, this is not a viable long-term solution, as these landfills are projected to reach capacity in the next 5-20 years. As an alternative, AquaX has designed a regional biosolids processing facility in Lewiston, Maine that destroys PFAS in sludge supplied by individual WWTFs around Southern Maine and reduces the volume of solids that must be landfilled. The company will employ a service-based model where WWTFs pay to have their waste treated on a per ton basis. After research into various technologies for PFAS sequestration and destruction, it was determined that supercritical water oxidation (SCWO) is the optimal technology for destroying PFAS compounds in sludge, as it is efficient and reduces the volume of solids. The SuperPro Designer software was utilized to generate proof-of-concept data for this process. Following treatment in a SCWO reactor, there are undetectable amounts of per-fluorooctane sulfonate (PFOS), the representative PFAS compound for modeling purposes, and 100% of the biosolids have decomposed to carbon dioxide, water, nitrogen, and sulfuric acid. An economic assessment has determined that the project would require an initial investment of $108 million, with a net present loss of $204 million over a 16-year lifetime and an annual loss of $14.9 million.

Example 3: Sustainable Mycoprotein Production via Hydrolysis and Fermentation of Coffee Waste
The global human population and associated carbon emissions continue to rise despite the dire need for plentiful and sustainable protein. Mycoprotein is one potential solution. Mycoprotein is typically produced by fermentation of pure sugar, but other industries are exploring the saccharification of waste products instead. A business that transforms an agricultural waste product, coffee silver skin (CSS), into edible mycoprotein is proposed. This novel process consists primarily of a delignification, hydrolysis, and fermentation reaction. Acidic hydrolysis was successfully demonstrated to produce reducible sugars with yields up to 52%. A process model was created in SuperPro to investigate the venture's financial viability. Based on this model, a plant capable of processing 898 MT of CSS into 730 MT of protein slurry annually is proposed. The final design includes a detailed safety analysis and control scheme. The plant would require a capital investment of $28.04 MM to yield a 26.5% return on investment over 12 years, making this project an attractive investment. A dramatic reduction in the environmental impact of agriculture is possible by realizing the cost-competitive production modeled.

4. Analysis of Student Outcomes

Students were given a Self-Assessment survey before and after the course that was broken into three parts. The first set of questions were on the capstone process design course outcomes asking them to indicate how they felt they knew a topic ranging from one being none to five being a lot. The course outcomes can be found in Table 1.

Table 1: Course Outcomes for CHME 4703 Capstone Design

1. Perform research to identify key aspects of a novel process design
2. Conduct project economic evaluations using capital and operating costs estimations for major items of equipment and select alternatives using economic decision methods
3. Conduct an assessment of intellectual property issues related to a design process.
4.Develop, read, and interpret flowsheets, process flow diagrams (PFDs), and piping and instrumentation diagrams (P&IDs).
5. Identify the use and limitations of process simulation in the design process
6. Prepare a preliminary process design to meet defined business, throughput, quality, and safety/environmental specifications, including identifying and specifying key process conditions
7. Initiate detailed design of major equipment items associated with fluid flow, separations, reactions, and/or heat transfer.
8.Design a process which holds paramount the safety, health and welfare of fellow employees, the public, and the environment.
9. Characterize the hazards associated with chemicals and other agents used in the design process, including toxic, flammable, and reactive hazards.
10. Identify and develop procedures to control and mitigate hazards to prevent accidents, including acute and chronic chemical releases and exposures, and including over-pressure protection of equipment
11. Identify the major regulations that impact the safety of chemical plants.
12. Perform a HAZOP or FMEA safety analysis of a design process.
13. Develop a proof-of-concept, experimental or simulated, of the design process
14. As a team, utilize oral and written communication skills for technical, managerial, and public audiences.
15. Practice time and project management to succeed in bringing a project to a successful conclusion on a timely basis.

Figure 1 shows the results from this set of questions from the survey, which demonstrated a positive, statistically significant increase in the outcomes of the course from beginning of the semester to the end. Of note, outcome 6, which is to make a preliminary process design meeting multiple factors including safety and environmental increased 68.7% from 2.79 before the course to 4.71 after. Outcome 8, looking at designing a process for the safety and health of public and the environment increased 59.2% from 2.94 to 4.69.

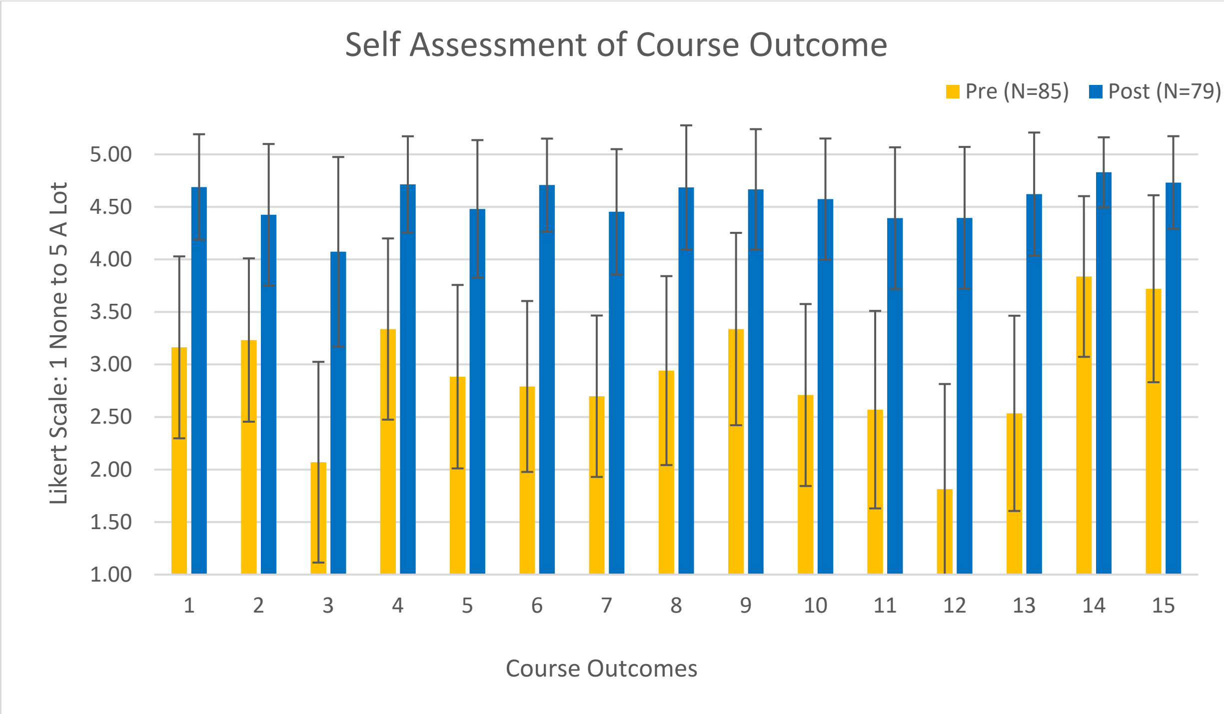

Figure 1: Results from student self-assessment survey of Capstone course outcomes from Spring 2024, all data points were found to be statistically significant from the pre to post course data with 85 students in the course.

The next set of questions had to do with social responsibility and were taken from the Engineering Professional Responsibility Assessment (EPRA) instrument which is a validated tool for assessing social responsibility[12], [13]. The questions, found in Table 2, asked the students if they believe that chemical engineers should consider certain attributes when considering process designs. They rated them from 1 as strongly disagree and 5 as strongly agree.

Table 2: Questions on social responsibility that came from the EPRA

I believe chemical engineers should..
1. Place utmost importance on human health
2. Be vigilant whether their research/design risks human safety
3. Consider the possible adverse effects on human health
4. Consider environmental protections during the design process
5. Minimize the effects on ecosystem
6. Promote sustainable development in the environment
7.Recognize the potential social problems in design

Figure 2 shows the results of the pre and post survey, which demonstrated increases in all questions except for number 7, which is about recognizing potential social problems in design. Though it shows that this question had the highest pre result of all the questions with a 4.65 out of 5 and therefore the post score of 4.68 did not change much at the end of the course. The first three questions on human health increased between 16% and 21%, demonstrating an increased awareness in designing for the betterment of human society. An increase of 13% for question 4 on environmental protections and 21% for question 5 on effecting ecosystems highlight that the course helped students realize the importance of the socio-environmental aspects of chemical engineering process design.

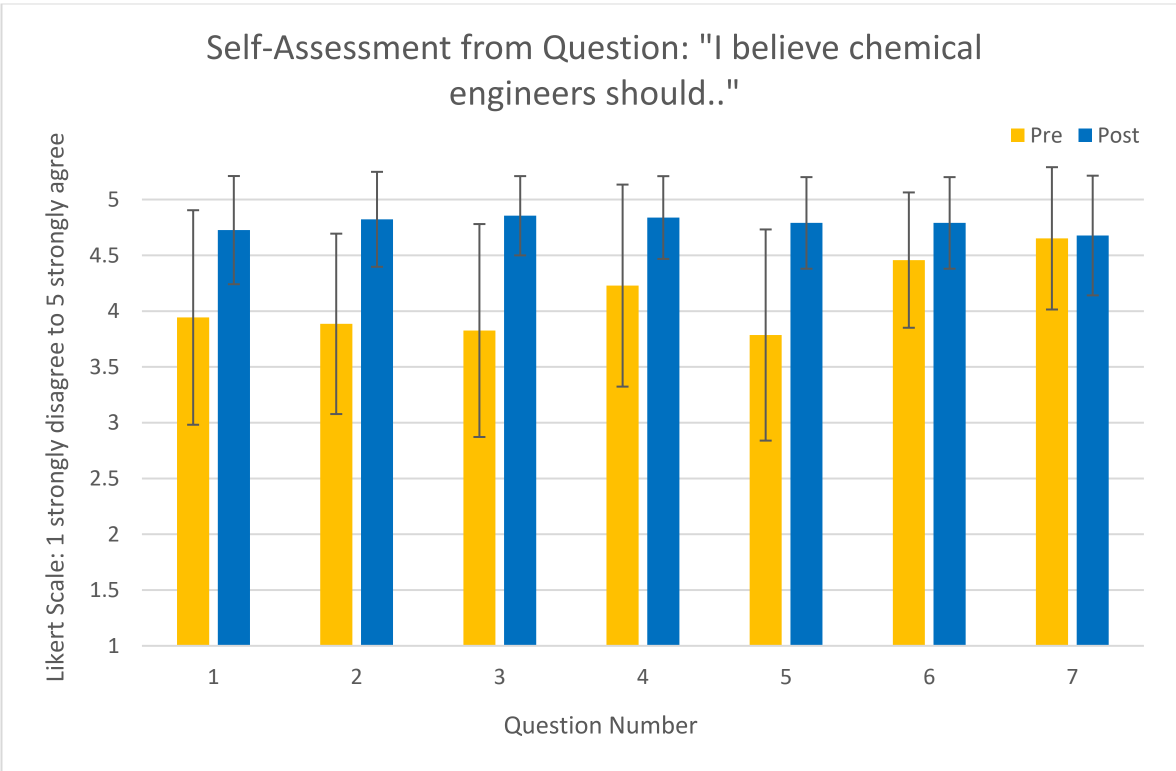

Figure 2: Results from the social responsibility set of questions. All data points were found to be statistically significant from the pre to post course data except question 7.

The last set of questions surveyed the students to understand their learning outcomes of sustainability. These questions came from Rekalde-Rodriguez et. al. on their Questionnaire to Assess Transversal Competencies for Sustainability[14]. These questions asked how well they are informed about the topics found in Table 3, from 1 not well at all to 5 extremely well.

Table 3: Questions from Self-Assessment of Sustainability Questions

1. Relating knowledge from different academic fields or subjects to identify problems and their possible solutions using a sustainable approach.
2. Discussing the implications of specific policies, programs or practices to pursue the Sustainable Development Goals (SDG) at the individual, social, cultural, environmental and/or global level.
3. Identifying opportunities and challenges for more sustainable development when planning measures linked to a specific context or area of study.
4. Identifying the needs of the economic and employment context, valuing dignity at work and setting an order of priority to favor employability.
5. Proposing actions, interventions and improvements, either individual or collective, which take into account the SDGs.

Figure 3 shows the results for the sustainability set of questions, which all showed statistically significant increases between 23% and 37%. The two questions that had the largest increase was question 2 on implications of policies to pursue the SDGs at the individual, social, cultural, environmental and/or global levels, which increased 37% from 2.49 to 3.4 and question 5 on proposing actions to take into account the SDGs with an increase of 33% from 2.61 to 3.48.

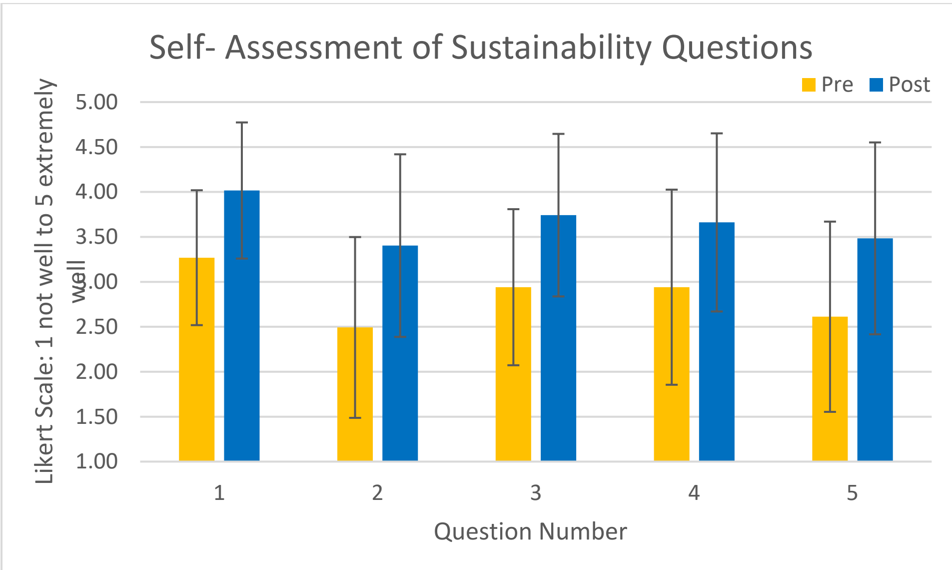

Figure 3:Results from the Questionnaire to Assess Transversal Competencies for Sustainability which were self-assessed by the students before and after the course. Note: all data points were found to be statistically different from the pre to post course data.

Analysis of the graphical data reveals key trends in student development. Figure 1 demonstrates a significant increase in self-reported competencies of the course learning outcomes, with over 80% of students reporting substantial improvement post-course. Additionally, Figure 2 highlights increased student agreement with the importance of social responsibility with marked increase in competencies regarding minimizing environmental impacts and promoting sustainable development practices in their designs. In terms of sustainability, Figure 3 shows a pronounced rise in students' ability to connect sustainability principles with policy and practice, indicating a stronger grasp of the global implications of their engineering designs. Notably, student confidence in discussing the implications of specific sustainability initiatives rose from an average rating of 2.7 (pre-course) to 3.6 (post-course) on a 5-point scale.

Students demonstrated a heightened ability to consider environmental and societal factors in their decision-making processes. They displayed a more comprehensive understanding of how design choices affect not only technical outcomes but also societal well-being. Awareness of global, social, and environmental challenges increased substantially, with students expressing a deeper understanding of their role as engineers in promoting sustainable development. Students gained valuable insights into the development and implementation of sustainable technologies, equipping them to address future challenges in chemical engineering.

7. Recommendation for Implementation

There are some key outcomes from the development of this sustainability, social responsibility focused-capstone course that can be implemented by other educators. First, looking at the types of project topics and sourcing. Try to find projects that combine engineering with ecological, social, and economic perspectives to develop holistic solutions. Sourcing projects from industry partners, alumni, and faculty that address pressing global challenges. These sources of projects can also help with technical support or guidance for students as they progress in their projects. Include life cycle analysis and environmental impact assessments as standard project components.

Secondly, emphasize entrepreneurial thinking. Require students to develop needs assessment, business plans and market analyses to understand the economic viability of sustainable solutions. This approach fosters an entrepreneurial mindset and prepares students for market-driven problem-solving and helps them scope and determine project feasibility early.

Thirdly, incorporate DEI practices by integrating discussions on diversity, equity, and inclusion into the course. Use team charters and evaluations to promote equitable participation and awareness of DEI in engineering practices.

Last of all, utilize iterative milestones. Implement structured project milestones like feasibility assessments, business plans, and detailed designs with frequent feedback from a variety of audiences. These checkpoints help guide students while ensuring thorough exploration of sustainability principles.

8. Conclusions

The redesigned capstone course has demonstrated significant success in integrating sustainability, social responsibility, and entrepreneurial thinking into engineering education. Students showed marked improvement in their ability to consider societal and environmental factors in their designs, as evidenced by self-assessment data and survey results. The inclusion of real-world projects and iterative design processes prepared students to address global challenges and develop market-ready solutions. By embedding these principles, educators can ensure students are well-equipped to meet the evolving demands of the engineering profession.
Future work should focus on assessing the long-term impact of this educational approach on graduates' career trajectories and their contributions to sustainable engineering practices.

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