LEVERAGING STUDENTS TO HELP GENERATE SENIOR PLANT DESIGN PROJECT TOPICS

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At the University of California Davis, the chemical engineering senior design sequence consists of three, four-unit courses offered in sequence over the period of one academic year. In the first course, entitled Process Economics and Green Design, students learn how a design idea is brought to concept, including how to assess design projects at various stages using rigorous profitability analyses, process safety considerations, and environmental/social considerations and constraints. In the second course, entitled Unit Operations and Separations, students learn heuristic and rigorous design of chemical process equipment, including design of pumps, pipes, compressors, reactors, heat exchangers, columns, and other separations equipment. Discussion and assignments related to use of Aspen Plus© are integrated throughout both courses. The final course, entitled Plant Design Project, is focused around the conceptual design of a chemical process, with emphasis on the flowsheeting, costing, and techno-economic evaluation of a complete industrial plant. Teams of four students address real-world plant design problems and report to their instructor roughly every two weeks in the form of memoranda, written design reports, and oral presentations. The first two courses in the design sequence are offered as single sections once per year in the Fall and Winter quarters respectively, and enrollments for both courses range from 100-150 students. The Plant Design Project course is run in multiple sections during the Spring quarter with 32-48 students enrolled per section depending on the size of the graduating class.

Offering modern and engaging senior design projects is a challenging and time consuming task for chemical plant design instructors.[1] Further, an offering of a chemical plant design project course may not include projects that align well with common interests within the cohort. In the past, an industrial colleague had helped to develop modern senior design projects. In addition to using these industry-inspired projects, the growth of the undergraduate student population has necessitated the development of an even greater number of new senior design projects.

Beyond this challenge, assessing students' ability to achieve the ABET, Inc, student outcomes[2-3] in capstone design courses is important as they are commonly used to satisfy ABET requirements.[4] In the Process Economics and Green Design course, the first course in the senior design sequence at the study institution, quiz and exam-type assessments have traditionally been used to assess course-level outcomes. Previous work has shown that project-based approaches to assessment can improve and better capture achievement of course-level student outcomes.[5,6] Involving students in the generation of design concepts is a project-based approach that has the potential to help students learn design thinking more effectively, as they will be exposed to the ideation aspect of design in addition to the realization and assessment of concepts.[7]

Informally, students at the study institution had indicated that they would enjoy more control over their senior design project topics so that they could explore their interests in greater depth. While using student-initiated topics for senior design projects is inherently risky, there is great potential for students to develop and practice creativity and entrepreneurial skills.[8,9] Despite the fact that most engineering educators agree that it is important to teach students to be creative thinkers in addition to teaching key engineering concepts, it has been shown that the engineering curriculum tends to discourage student creativity.[9] Further, it has been shown that students' ability to generate novel ideas is related to their individual tolerance for ambiguity.[9] Assigning students to generate design project topics would require them to think

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creatively in proposing a solution to an open-ended prompt and to start developing a tolerance for ill-defined problems.

During the Fall 2016 quarter, in lieu of a mid-term examination, a project-based approach to assessment was piloted, where students were tasked with proposing their own senior design project idea for potential use in the Plant Design Project course.[10] This chemical plant design project proposal assignment was designed to better require use of and assess key skills taught in the Process Economics and Green Design course, including the ability to carry out a literature survey, develop a chemical process idea, and carry out an input/output (I/O) analysis. The risk associated with allowing the students to propose their own senior design project topics was mitigated by not committing to allow the students to take their ideas beyond the Fall quarter course.

Involving students in project idea generation was also the goal of a recent effort at the University of Michigan to revitalize the chemical engineering senior design experience.[8] The authors assigned groups of three students to pitch teams that generated senior design project ideas and presented them to their peers.[8] Larger groups of students were assigned to the winning projects.[8] Similar to this work, the project was assessed in part using student ratings of selected ABET student outcomes.[8] In this work, a comparable assignment was evaluated using direct assessments and indirect assessments of select ABET student outcomes. Further, the difference in responses to survey questions based on gender and under-represented minority (URM) status was investigated.

Preliminary results from the pilot year suggested that the plant design project proposal assignment was effective in both enhancing the students' appreciation for how a chemical plant design project idea is developed and allowing the students to achieve the desired ABET student outcomes.[10] There were also indications that aspects of the assignment were particularly beneficial to female and URM students. The students proposed a variety of interesting plant design project topics, and three new student-initiated senior design projects were developed for the Plant Design Project course in Spring 2017. This assessment method has now been used during the past two academic years and has been completed by over 300 students. In this paper, data collected over these two years were aggregated and analyzed in order to assess the effectiveness of this assignment as well as achievement of select ABET student outcomes. Preliminary results from the pilot year were reevaluated using the larger sample size.

DESCRIPTION OF THE PROJECT

On day one of their senior year, students were assigned to complete a design project proposal in the Fall quarter Process Economics and Green Design course, and they were told that their idea may be used as a plant design project to be completed later that academic year. This design project proposal assignment required students to describe a potential design project idea, clearly stating how the idea was significant and unique. They were required to present a survey of the relevant literature, establish the theoretical basis on which the proposed process was built, identify potential safety concerns, identify current competitive technologies, and prove that a market for the proposed product exists. They had to describe important process alternatives, including potential raw materials and reaction pathways as examples. Finally, a preliminary assessment of the design alternatives was made using I/O level economic, environmental, and social assessments. An evaluation of the results was made by the students, and they concluded by recommending that the project should or should not be considered in more detail as a senior design project. The best proposals were considered for implementation as senior design projects in the Plant Design Project course. As this project was developed and implemented from 9/2016 – 12/2017, ABET student outcomes 3A-K[2] were mapped to the project criteria a-f (capital letters refer to ABET student outcomes and lower case letters refer to project criteria). Mapping the project criteria to new ABET outcomes 1-7 is discussed later.

Student performance on the assignment was assessed on the basis of the student's ability to 1) communicate effectively (ABET Student Outcome G), 2) describe a preliminary process design concept that met a societal need within realistic constraints (ABET Student Outcome C), 3) understand ethical responsibilities and potential safety issues (ABET Student Outcome F), 4) understand the impact of the proposed design project in a global, environmental, and societal context (ABET Student Outcome H), 5) gain a knowledge of contemporary issues (ABET Student Outcome J), and 6) gain an ability to engage in life-long learning by immersing themselves in the literature (ABET Student Outcome I). The student outcomes were integrated into six criteria for which students were judged to have met, exceeded, or been deficient. The criteria and related outcomes (from the list above) included:

a. *The problem statement and significance of the project were clearly explained. Related theory and works in the literature were presented and cited (Student Outcomes C, H, I, and J).*

b. *Potential environmental impacts, societal impacts, and safety hazards were detailed (Student Outcomes C, F, and H).*

c. *Potential process schemes were evaluated, including different combinations of raw materials, different reaction pathways, and configurations of unit operations. Criteria that would be used to assess these alternatives were also discussed (Student Outcomes C and I).*

d. *Potential profitability of the process was assessed based on raw material selection and I/O analysis. The market for the product(s) and other revenue generating streams* *was discussed (Student Outcomes C and I).*

e. A clear recommendation as to whether the project should be considered in more detail was made. This recommendation was based on the I/O economic assessment, as well as on environmental and social measures. It was also made clear which process alternative(s) were viable, if any (Student Outcomes G and H).

f. The proposal was delivered in a neat and logical format. Figures were clear and readable. References were cited correctly and presented in a bibliography (Student Outcome G).

Students were allowed eight weeks to complete the assignment, which was worth 40% of their course grade. The criteria on which their projects were to be assessed was distributed to the students along with the assignment. During the pilot year, students submitted individual ten-page papers detailing their proposals. For the second iteration of the assignment, submissions were required to be in video format with a maximum run-time of five minutes. Further, each proposal during the second iteration was completed in groups of two students. These changes were made to allow students to practice working in groups prior to their spring plant design project as well as to allow them to be more creative with how they presented their project proposal. The instructors did not find the video format to be problematic in any way, as the students were required to present their I/O calculation within the video as well as submit a list of references including their sources for pricing information.

During the eight weeks of preparation, the students were taught the hierarchical method to process design, including how to develop design project ideas, how to assess projects at various stages of development using economic, environmental, and social/safety indicators. Students had access to regular office hours with the two course instructors, special project-focused office hours sessions with one of the instructors, and periodic consultation sessions with an industrial consultant. For the second iteration of this assignment, an abstract was required three weeks into the course in order to verify that each group was working on an acceptable topic as well as making sufficient progress.

DATA COLLECTION AND ANALYSIS

Student outcomes were directly assessed via the six project criteria using a five point rubric, as defined in the Appendix (see Table A1). Students were judged to have achieved the outcomes associated with each criteria by earning a B-level score or better, indicating that the students at least met the majority of the criterion with only minor errors present. Due to the large enrollment for this course, multiple graders were involved in grading these projects. For consistency, only the assessment results from the instructor were analyzed. Thus, this sample included eighty-seven out of three hundred and nine submissions (28%).

After the completion of the assignment, students were voluntarily surveyed to assess their perception of the effectiveness of the assignment as a measurement of their ability to develop a preliminary design idea. They were also surveyed to measure their perception of how strongly the ABET student outcomes for the course mapped to this assignment. On the survey, the students were asked to respond to a series of statements using a Likert-type scale to specify their level of agreement or disagreement with each statement. The statements included on the survey can be found in the Appendix. Although achievement of select ABET student outcomes was specifically targeted by this assignment, as outlined in the previous section, the students were asked to specify their level of agreement or disagreement regarding achievement of all of the course-level ABET student outcomes using this assignment so that comparisons could be made.

The students were also given the opportunity to provide freeform comments on the survey in response to the following questions:

1. *What do you feel was the most useful aspect of this assignment?*
2. *What about this assignment do you feel needs the most improvement?*
3. *What other feedback do you have regarding the design project proposal assignment?*

The students were asked on the survey to optionally provide their demographic information including gender and ethnicity. For the students electing to respond to these questions, the survey responses were segregated by gender and URM status in order to compare the responses to the survey questions between these groups. Average responses were calculated for the survey statements requiring a Likert-type scale response by equating the response "strongly disagree" to 1, "disagree" to 2, "neutral" to 3, "agree" to 4, and "strongly agree" to 5. In order to make comparisons between the Likert-type scale responses to the survey questions, the number and percentage of responders who selected each Likert-item for a given question were compared.

RESULTS AND DISCUSSION

Figure 1 shows the direct assessment results for the six project criteria during years 1 and 2. Students were judged to have achieved the outcomes associated with each criteria by earning a B-level score or better. Students generally earned higher grades during year 2, potentially due to better communication of expectations by the course instructors and completion of the project in groups. Satisfactory completion of criterion a (problem definition and literature review) was especially high during year 2, which could be linked to feedback received on an abstract that was submitted five weeks prior to the project deadline. Satisfactory completion of criterion f (neatness/organization) declined during year 2, which could be associated with the project format being changed from a written report to a video submission.

One hundred forty six students enrolled in the course in either Fall 2016 or Fall 2017 responded to the end-of-project survey out of a possible three hundred nine (47% response rate). One hundred fourteen of the one hundred forty-six responders (78%) either agreed or strongly agreed that the assignment gave them a better appreciation for how a chemical engineering plant project idea was developed. Only twelve responders (8%) did not feel that they achieved this outcome. Eighty-eight of the responders (60%) either agreed or strongly agreed that the assignment was a good assessment tool for the material learned in the course while only 19% of responders disagreed with this statement. These responses are illustrated in Figure 2. Agreement for the assignment being a good assessment tool increased significantly in year 2 (only 50% agreed after year 1), whereas agreement with the "better appreciation" statement remained the same on a percentage basis.

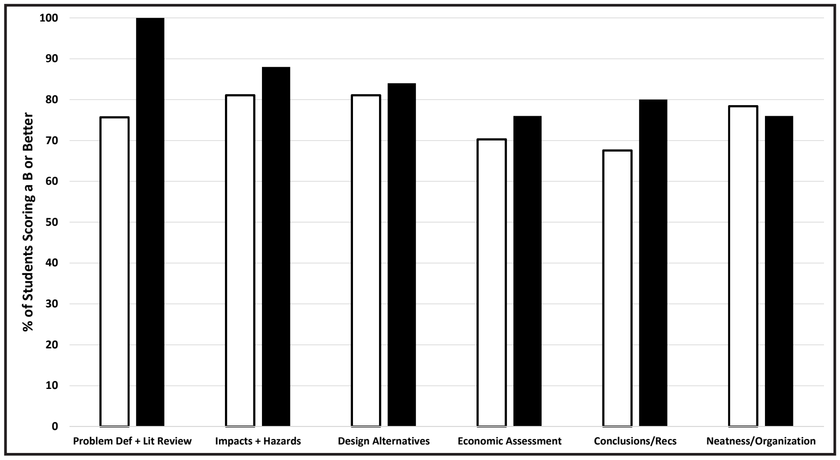

Figure 1. Direct Assessment of Project Criteria. *Students were assessed on six criteria (defined as criteria a-f above) using a five-point scale. A sample of submissions graded by the same instructor from year 1 (white) and year 2 (black) was analyzed.*

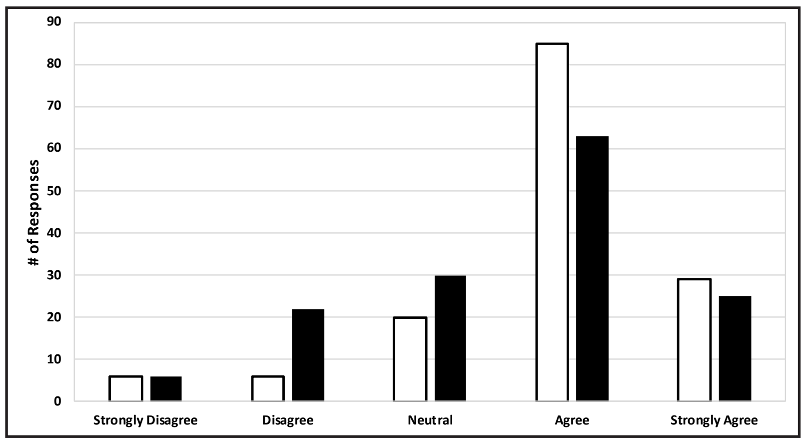

Figure 2. Overall student rating of the plant design project proposal assignment. *Students (n=146) provided responses on a Likert-type scale to the statements "This assignment gave me a better appreciation for how a chemical engineering plant project idea is developed" (white) and "I feel that this assignment is a good assessment tool for the material learned in this course" (black).*

As a cohort, the students felt most strongly that they achieved ABET Student Outcomes H (understanding the impact of engineering solutions, 84.3% of responders agreed or strongly agreed) and J (knowledge of contemportary issues, 74% of responders agreed or strongly agreed). These results are shown in Figure 3, where the distribution of responses to selected student outcomes for which perceived achievement was especially high or low as compared to other student outcomes is shown. Achievement of these student outcomes aligns with the expectations of this assignment. Other student outcomes that were targeted included Student Outcome C (design, 63.7% of responders agreed or strongly agreed), Student Outcome F (ethics and professional responsibility, 68.5% of responders agreed or strongly agreed), Student Outcome G (written and oral communication, 64.4% of responders agreed or strongly agreed), and Student Outcome I (lifelong learning, 69.2% of responders agreed or strongly agreed). Overall, a strong majority of students felt that they were achieving the ABET student outcomes that are tied to this assignment.

Students rated achievement of ABET Student Outcomes A (application of math, science, and engineering, 52.7% of responders agreed or strongly agreed) and E (formulate and solve engineering problems, 45.9% of responders agreed or strongly agreed) the lowest of all of the survey questions. These ABET student outcomes were not specifically targeted by this assignment, but these skills are required in order to develop such a project proposal. It is believed that students tend to associate these student outcomes with solving "problem set" type problems, and that some may not appreciate how these skills are applied to solving open-ended and ill-defined problems when encountering them for the first time.

Distinct variations in responses to survey statements correlating to targeted ABET student outcomes were observed when the data was segregated by gender and URM status. It must be noted that these differences in responses were not found to be statistically significant as determined using a chi-squared test (p-values were all greater than 0.05). Figure 4 illustrates the differences in response to select questions based on gender. Female students were more likely to agree or strongly agree that they had achieved Student Outcome

F (ethics and professional responsibility, $\chi^2 = 0.42$, $p > 0.51$) and Student Outcome G (communication, $\chi^2 = 2.07$, $p > 0.15$) at a rate of 5% and 12% more than male students respectively, consistent with results obtained during the pilot year. Conversely, male students were more likely to agree or strongly agree that they had achieved Student Outcome I (lifelong learning, $\chi^2 = 1.19$, $p > 0.27$) and that they gained a better appreciation for how a chemical engineering plant project idea is developed ($\chi^2 = 1.96$, $p > 0.16$) at a rate of 9% and 10% more than female students, respectively. This result for the "better appreciation" statement was appreciably different than results obtained during the pilot year, where female students rated their achievement of this student outcome higher than male students. Fourteen of the 146 responders did not disclose their gender and were not included in this analysis.

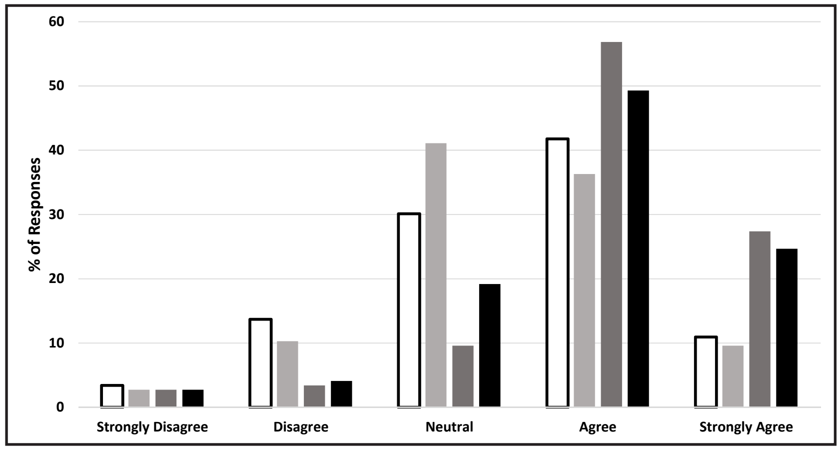

Figure 3. Student rating of ABET student outcome achievement via the plant design project proposal assignment. *Students (n=146) provided responses to survey statements gauging their perceived achievement of ABET student outcomes using a Likert-type scale. Student Outcomes depicted include Student Outcome A ("applications": white), Student Outcome E ("problem solving": light grey), Student Outcome H ("impacts": dark grey), and Student Outcome J ("contemporary issues": black).*

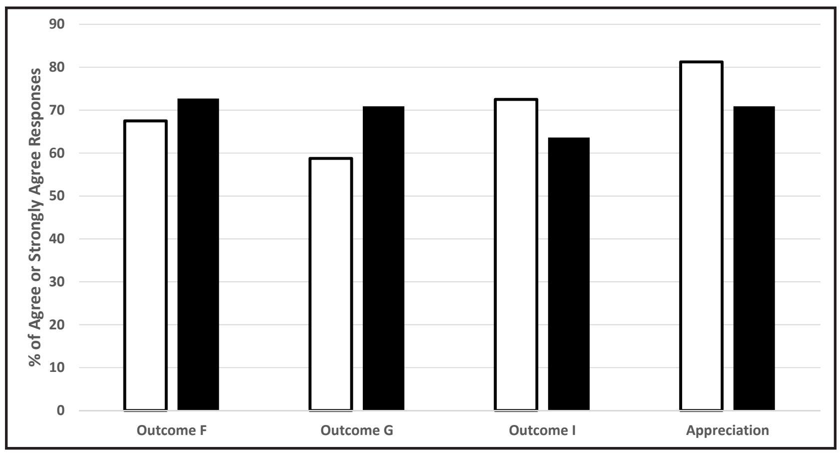

Figure 4. Differences in responses to select ABET student outcome questions based on gender. *The percentage of agree or strongly agree responses to survey statements correlating to select targeted ABET student outcomes were segregated into male responders (n=80, white) and female responders (n=55, black).*

Figure 5 illustrates the diffences in response to select questions based on URM status. URM students were more likely than non-URM students to agree or strongly agree that they had achieved Student Outcome F (ethics and professional responsibility, $\chi^2 = 2.84$, $p > 0.09$), Student Outcome I (lifelong learning, $\chi^2 = 1.35$, $p > 0.24$), and that they gained a better appreciation for how a chemical engineering plant project idea is developed ($\chi^2 = 1.59$, $p > 0.20$) at a rate of 19%, 13%, and 12%, respectively. Conversely, non-URM students were more likely to agree or strongly agree that they had achieved Student Outcomes C (design, $\chi^2 = 2.63$, $p > 0.10$) and G (communication, $\chi^2 = 0.77$, $p > 0.38$) at a rate of 19% and 10%, respectively. These results were also consistent with what was observed during the pilot year alone. Eighteen of the 146 responders did not disclose their ethnicity and were not included in this analysis.

In response to the freeform survey questions, the students indicated in general that they enjoyed the freedom of choosing their own topic so that they could be creative and find out what aspect of chemical engineering they are truly interested in. Sample comments included:

> *Having the freedom to choose any topic was extremely useful because it allowed me to really analyze what I actually care about and can potentially use my major to affect change.*

> *I feel like this project helped everyone figure out what field they're interested in and learn more about that field.*

> *I liked this project because it gave us real life situations to work with. It was a lot more useful than only researching topics.*

> *The research aspect was most useful, as well as learning how to piece together information to create a cohesive project.*

They also learned some practical lessons along the way. Sample comments included:

> *I learned that a cool idea doesn't necessarily make money.*

> *I didn't realize how much work went into plant design.*

Many students also indicated that the open-ended nature of the assignment made it difficult to know what was expected in their submission. Sample comments included:

> *I understand the idea of having the assignment open ended was to spur creative response from the class; however, in this case some more structure and instructions would have been helpful.*
>
> *The assignment needs more directions, as this is our first time approaching a problem of this magnitude.*
>
> *The quality of the report was very dependent on the complexity of the idea. Thus, it was hard to write a design proposal with a well thought out design. It felt more of a writing exercise as opposed to an engineering & writing exercise. The idea of the assignment was promising, but it was difficult to formulate a well thought out and unique proposal.*

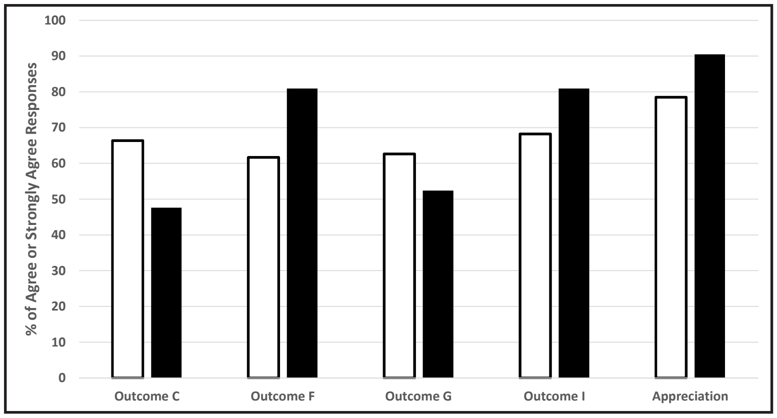

Figure 5. Differences in responses to select ABET student outcome questions based on URM status. *The percentage of agree or strongly agree responses to survey statements correlating to select targeted ABET student outcomes were segregated by URM status into non-URM responders (n=107, white) and URM responders (n=21, black).*

The students have generated a number of interesting senior design project ideas over the two iterations of this assignment, a few of which are listed in Table 1. After the proposals were assessed, the instructors and an industrial consultant worked to identify proposals that were well suited to be offered as full plant design projects. Selected proposals had to be reasonable in scope so that they could be completed in the ten weeks allotted for the Plant Design Project course. The process also had to include at least one chemical reaction and the majority of the unit operations needed to be able to be sized in Aspen Plus©. The instructors looked for themes in the topics of the proposals submitted and, when possible, defined the full design projects in a way that captured a number of students' ideas. An example of this was for the gasification of biomass (to produce hydrogen) project, where many proposals dealt with the gasification of various types of biomass. Within this project, different design teams were assigned to investigate the gasification of a different biomass in order to produce the hydrogen product.

Recently, ABET has defined a new set of student outcomes (outcomes 1-7) and has begun requiring engineering programs to assess these new outcomes in lieu of outcomes a-k.[3] The criteria for this assignment, defined previously, readily map to these new student outcomes. Specifically, to successfully complete this project, students are required to describe a preliminary process design concept that meets specified needs with consideration of public health, safety, and welfare, as well as global, social, environmental, and economic factors (Outcome 2), communicate their project effectively (Outcome 3), understand their ethical and professional responsibilities with respect to the project and make informed judgements which consider economic, environmental, and social impacts (Outcome 4), and acquire and apply new knowledge (Outcome 7). For the second iteration of the assignment, as students were required to work in teams, Outcome 5 (ability to function effectively on a team) would also apply.

TABLE 1
Examples of Student Design Project Proposals

Examples of Proposals Selected to be Full Design Projects	*Hydrogen production by gasification of biomass and waste feedstocks* *Light olefin production from syngas by the OX-ZEO process* *Optimization of a water desalination plant*
Examples of Creative Proposals not Selected to be Full Design Projects	*Manufacturing bio-based epoxy resin from itaconic acid* *Production of naloxone to be administered to victims of an opioid overdose* *Conversion of waste carbon dioxide and carbon monoxide into acetic acid and acetic acid derivatives*

CONCLUSIONS

The plant design project proposal assignment has been effective in both enhancing the students' appreciation for how a chemical plant design project idea is developed and allowing the students to achieve targeted ABET student outcomes. There also have been indications that aspects of the assignment continue to be particularly beneficial to female and URM students. The students have proposed a variety of interesting plant design project topics over the two iterations of this assignment, and three new senior design projects per year have been developed for the Plant Design Project course that were initiated by these student project proposals.

ACKNOWLEDGEMENTS

I would like to thank my senior design co-instructor, Professor Ahmet Palazoglu, for his mentorship and support of this project. I would also like to thank Mr. Andy Towarnicky from Marathon Petroleum for mentoring our students during this project as well as helping us define senior design projects from these proposals.

APPENDIX

TABLE A1
Grading Rubric Used to Separately Assess Each of the Project Criteria

Grade Range	**Description**
A	The submission completely satisfied the criterion.
B	The submission met the majority of the criterion, with minor errors.
C	The submission did a fair job with respect to the criterion, with errors present.
D	The submission was deficient with respect to the criterion, with major errors present.
F	The submission was severely lacking in content/quality.

Survey Statements

Students indicated their response to the following statements by selecting one of the following options: Strongly Disagree, Disagree, Neutral, Agree, or Strongly Agree

This assignment gave me a better appreciation for how a chemical engineering plant project idea is developed.

This assignment has enhanced my ability to apply my knowledge of mathematics, science, and engineering.

This assignment has enhanced my ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.

This assignment has enhanced my ability to identify, formulate, and solve engineering problems.

This assignment has enhanced my understanding of professional and ethical responsibility.

This assignment has enhanced my ability to communicate effectively.

This assignment has enhanced my understanding of the impact of engineering solutions in a global, economic, environmental, and societal context.

This assignment has helped me recognize the need for, and enhance my ability to engage in life-long learning.

This assignment has enhanced my knowledge of contemporary issues.

This assignment has enhanced my ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

I feel that this assignment is a good assessment tool for the material learned in this course.

Students provided freeform comments in response to the following:

What do you feel was the most useful aspect of this assignment?

What about this assignment do you feel needs the most improvement?

What other feedback do you have regarding the design project proposal assignment?

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