CASE-BASED LEARNING IN MATERIAL AND ENERGY BALANCES TO HELP STUDENTS PRACTICE THE TRANSFERABILITY OF CHEMICAL ENGINEERING PROBLEM-SOLVING

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INTRODUCTION

More and more students graduate from chemical engineering programs and head into careers beyond traditional chemical engineering (i.e., commodity chemicals).[1] As such, there is a growing need for curricula and faculty to better prepare students to apply their problem-solving skills to a wider variety of problems and fields, and expose students to the possibilities of chemical engineering training beyond the plant or refinery. Drawing on a wider range of examples allows for greater student motivation, which is an important factor for academic success in chemical engineering.[2] Thus, a major driver for improving our course was to consider how we can help students see chemical engineering thinking as a more transferable and useful skill beyond the classroom, which is a known challenge when using traditional chemical engineering problems.[3] This is not a new idea in chemical engineering education, having been advocated in previous calls for curricular change from the turn of the century,[4] and continued innovation in effectively implementing pedagogical strategies to aid in this transfer of chemical engineering skills are still being sought.[5]

Since Fall 2019 we have begun implementing case-based learning within our Material and Energy Balances (MEB) course to help students focus on the transfer of their burgeoning chemical engineering skills to real-world problems. In supporting student growth towards this goal, teaching with cases – "stories told with an education purpose"[6] – allows students to apply their learning by analyzing historical, contemporary, or hypothetical situations that require students to make decisions or solve problems.[7] Cases serve as an opportunity for students to practice as if they were in the field, in a context that can be more motivating and relevant to them.[6] In chemical engineering, teaching with cases has also been noted in helping students feel more a part of the chemical engineering community – a pedagogical approach that can help programs move towards their DEI goals.[8]

Case-based instruction is a pedagogical approach common in law, medicine, and business but is relatively less common in science and engineering.[9] The National Center for Case Study Teaching in Science (NCCSTS) at the University at-Buffalo promotes STEM case instruction and maintains the Case Collection – a peer-reviewed case database with the National Science Teaching Association. Many of the sciences have a large number of cases, with 100+ chemistry entries in the collection's 1000+ cases, for example. However, the NCCSTS Case Collection houses a paltry 13 chemical engineering cases as of Fall 2022, only five of which are appropriate at the introductory level.[10] Other sources for chemical engineering pedagogical resources (e.g., AIChE Concept Warehouse [11] and LearnChemE [12]) host few cases.

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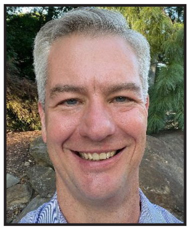


The limited availability of chemical engineering cases shows the benefit to our field of the development of relevant case studies, especially at the introductory level where student experience is highly correlated with persistence and motivation within the major.[13]

The most notable examples of cases focused on material and energy balances are those that are included near the end of Felder and Rousseau's popular *Elementary Principles of Chemical Processes* textbook – three examples in each edition that integrate material and energy balances content into real-world problems – comprising chapters 12-14 of the 3rd edition.[14] These cases provide deep detail into real chemical processes and guide students through the end of chapter questions to investigate technical elements of these processes. A few of these questions also ask students to make decisions or discuss elements of the processes. However, cases are not included in the most recent edition of the textbook as they had been in the previous versions,[15] which points to the usefulness of producing and sharing cases that could be used across an MEB course and not only as an capstone exercise at the end of the curriculum.

In this paper we share how we have implemented case-based learning in our MEB course at a variety of different scales and provide data to show the effect of implementation on student learning and course experience – both in the first iteration of the course with cases and when the use of cases has become more mature. Our intent in sharing is not to convince the reader that our approach is the only way to integrate case-based activities into the chemical engineering classroom, but instead to help inspire and convince more of our colleagues to try using cases as another tool to engage students in learning chemical engineering.

COURSE DESIGN

At Columbia University, the MEB course is the first technical course students take in the major and may be the first course students take that engages in numerical engineering problem-solving. The course primarily focuses on the application of material and energy balances to the analysis of process flows with the course-level learning objectives shown in Table 1. Enrollment averages 30 students each year – a mix of sophomores and transferring juniors. There has been continuity in instructors teaching this course since Fall 2018, with implementation of case-based instruction starting in Fall 2019, when all instruction was in-person.

Cases continued to be used during the transition to remote teaching (Fall 2020), during hybrid instruction (Fall 2021), and when we returned to in-person teaching (Fall 2022). During the transition to remote teaching in Fall 2020, the course was flipped, making more space for active learning (such as case-based learning) and for students to form social connections with one another,[16] a structure of the course that was maintained even with the return to fully in-person instruction in Fall 2022. This additional change in the course design in Fall 2020, however, limits our ability to determine how student learning and experience were affected by the introduction of case-based pedagogies.

TABLE 1
Course Learning Objectives

By the end of the course, students will be able to…	
LO1.	Explain how chemical engineers approach problems, and the roles they serve across industries.
LO2.	Propose quantitative solutions to a variety of complex problems using approaches familiar to chemical engineers (e.g., balance equations).
LO3	Critique solutions and determine the qualities of stronger answers through a chemical engineering lens.

We decided to implement material and energy balances cases at a variety of time scales, the cover a variety of sectors (e.g., commodity chemical, energy and the environment, biopharmaceutical), and place students as chemical engineers in a variety of roles (both traditional and nontraditional). The shorter of these cases was run as an in-class activity (~50 minutes) that displaced time that was previously allocated to lecture (typically instructor-guided problem-solving or example applications of course concepts). Other cases were assigned as homework (weeks-long) – with case-based problems replacing additional problems on a problem set and as a month-long final project.

In-Class Case Activities

The shortest cases are run as in-class activities (~50 minutes) where students are placed in more traditional chemical engineering contexts (e.g., process engineering) and tasked with making a process design decision. Students are guided during the following discussion to find contexts in which their choices may differ, even with the same calculated results. For instance, the first case activity in which students engage is to select between synthetic pathways for the production of amino acids that differ in production and safety, an excerpt of which can be found in Figure 1. This is not an uncommon trade-off that chemical engineers may need to consider. Other examples include improving the efficiency of chemical reactors and specifying the heat requirement of industrial furnaces. These activities replaced class time that was previously used for lecture.

Each case activity presents the problem as a story with named characters who present or share information in a way that students may encounter in engineering practice. In the example shown in Figure 1, representatives from manufacturing and chemical synthesis teams are used both as an example of teams students may interact with as process engineers, but also as a vehicle for the conflicting priorities between which students may have to choose. These cases are supplemented with guiding questions for students on a worksheet where students can write notes and answer questions.

After giving student teams time to discuss, instructors then engage with student teams who have questions or check in on their progress. After about 20 minutes of working the case, students submit their team's response in some way. For the example of amino acid production in Figure 1, teams register a vote in a Google® Doc for which of the two pathways their team has selected along with their reasoning for the decision. Instructors then lead a class discussion with and between students, first to align on the numerical calculations needed to address the case (i.e., atom economy and process economy for the amino acid case) before leading a debate that relies on individual interpretation of the calculations and data. Class discussion often lasts 20-30 minutes, with the totality of the in-class activities taking around 50 minutes.

Producing Amino Acids

Case Background

At your job as a chemical engineer in the process development group at LionChem, your boss, Natalie, asks you to join a group discussion to help decide how the company should pursue the production of amino acids at the plant. You are presented two synthetic methods to do so, the (unbalanced) reactions shown in Table A.

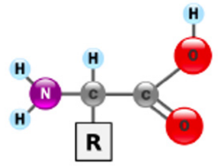


Figure 1. Amino Acid Structure

Table A. Two Pathways for the Chemical Synthesis of Amino Acids

Strecker Synthesis	**Bucherer Synthesis**
$RCHO + NH_3 \rightarrow H_2NCH(R)OH$	$RCHO + NaCN + (NH_4)_2CO_3 \rightarrow RC_3H_3O_2N_2 + NaOH + NH_3$
$H_2NCH(R)OH + HCN \rightarrow H_2NCH(R)CN$	
$H_2NCH(R)CN \rightarrow H_2NCH(R)COOH + NH_3$	$RC_3H_3O_2N_2 \rightarrow H_2NCH(R)COOH + CO_2 + NH_3$

Where R is the side chain of the amino acid.

As the meeting progresses, members of the two different teams at the plant – Robby from manufacturing, and Sun from chemistry – get into a discussion over which of the two processes they would prefer.

Sun: "Given how easy it was for our team to run these reactions at the lab scale, we feel that the Strecker process is the direction we should move toward for full-scale production. Additionally, we believe the Strecker process will produce less waste."

Robby: "The process may work well at the lab scale, but I am concerned about process safety at full scale with some of the reagents our team would be working with in the Strecker process. Because of that, we would prefer to pursue the Bucherer process instead."

Natalie turns to you. "Since we have a stalemate between manufacturing and chemistry, I'll leave it to you and the process development team to decide which of the two processes we should choose. For our next meeting, why don't you come present a short summary defending which process you'd choose and why you agree with Robby or with Sun?"

Figure 1. *Example case for in-class case activity for students, where students need to make a decision between synthetic pathways for the production of amino acids.*

Group Case Homework

As an intermediary scale, cases are assigned as team homework assignments. During these cases, students are placed in roles beyond what may be seen as traditional chemical engineering jobs to address open-ended questions based on current events. Teams of 4-5 students are given two weeks to draft a short slide deck (5-10 slides) with their proposals that are later peer reviewed. Students are provided a suggested form for the deck to help guide its preparation, as the second-year students in the course were not expected to have much, if any, experience with the preparation of such a presentation. Group case homework includes pitching potential chemical products as an entrepreneur and advising Congress on incentivizing alternative fuels as an AAAS Fellow. An excerpt of the group case homework where students pitch chemical targets that use carbon dioxide and excess solar power is shown in Figure 2.

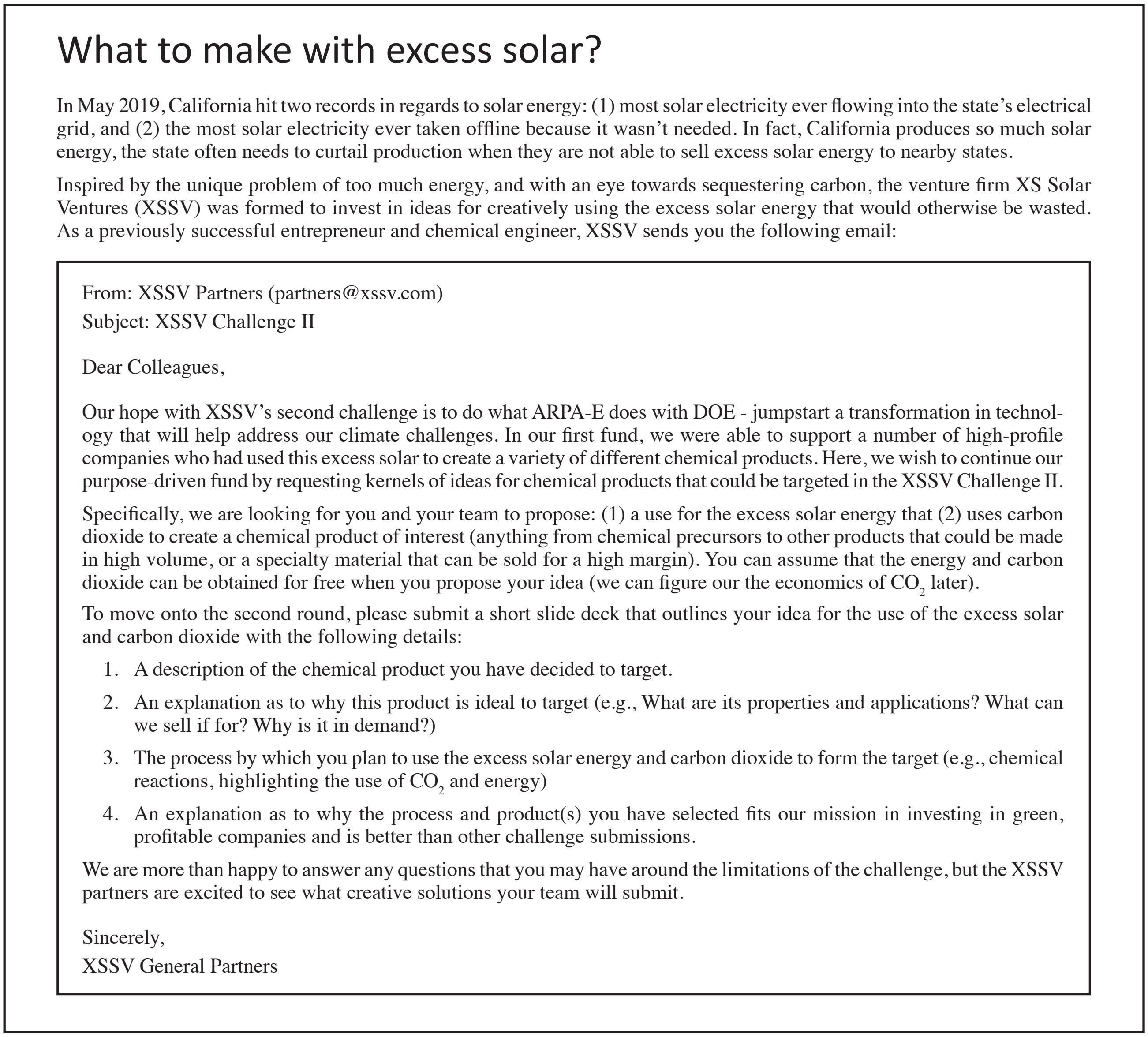
Group case homeworks are submitted in between quantitative problem sets. As such, the problem set preceding the case homework has been shortened to give time for students to complete the group case homework. Additionally, to give students practice critiquing each other's solutions and providing feedback, students each peer review two other team's submission in the week after the group case homework are submitted using a rubric as a guide.

Final Project Cases

Finally, as the longest time scale, cases in the course are assigned as final projects. During the last month, student teams (4-5) are tasked with advising on a case based on unproven technologies in a written report that draws on concepts from throughout the class. Selecting contemporary challenges assures that right answers are unknown and allows students to focus on their argumentation using chemical engineering approaches over "correctness." Previous final projects in our class include:

- Evaluation of a pyrolysis process for carbon sequestration (covered in Fast Company [17]) in partnership with Charm Industrial
- Analysis of Proton Technology's Blue Hydrogen Production (covered in Science [10])
- Metalysis of regolith (moon rocks) into aluminum and oxygen using the FFC Cambridge process as described in the novel *Artemis* by Andy Weir [18]

For each of these project cases, students are required to prepare block flow diagrams and associated stream tables that capture the process as they understand it to be based on the case. Students delineate the assumptions that lead to their material and energy balance calculations and give a recommendation based on their calculations in the context of the problem. Instructors provide feedback on the students'



What to make with excess solar?

In May 2019, California hit two records in regards to solar energy: (1) most solar electricity ever flowing into the state's electrical grid, and (2) the most solar electricity ever taken offline because it wasn't needed. In fact, California produces so much solar energy, the state often needs to curtail production when they are not able to sell excess solar energy to nearby states.

Inspired by the unique problem of too much energy, and with an eye towards sequestering carbon, the venture firm XS Solar Ventures (XSSV) was formed to invest in ideas for creatively using the excess solar energy that would otherwise be wasted. As a previously successful entrepreneur and chemical engineer, XSSV sends you the following email:

From: XSSV Partners (partners@xssv.com)
Subject: XSSV Challenge II

Dear Colleagues,

Our hope with XSSV's second challenge is to do what ARPA-E does with DOE - jumpstart a transformation in technology that will help address our climate challenges. In our first fund, we were able to support a number of high-profile companies who had used this excess solar to create a variety of different chemical products. Here, we wish to continue our purpose-driven fund by requesting kernels of ideas for chemical products that could be targeted in the XSSV Challenge II.

Specifically, we are looking for you and your team to propose: (1) a use for the excess solar energy that (2) uses carbon dioxide to create a chemical product of interest (anything from chemical precursors to other products that could be made in high volume, or a specialty material that can be sold for a high margin). You can assume that the energy and carbon dioxide can be obtained for free when you propose your idea (we can figure our the economics of CO_2 later).

To move onto the second round, please submit a short slide deck that outlines your idea for the use of the excess solar and carbon dioxide with the following details:

1. A description of the chemical product you have decided to target.
2. An explanation as to why this product is ideal to target (e.g., What are its properties and applications? What can we sell if for? Why is it in demand?)
3. The process by which you plan to use the excess solar energy and carbon dioxide to form the target (e.g., chemical reactions, highlighting the use of CO_2 and energy)
4. An explanation as to why the process and product(s) you have selected fits our mission in investing in green, profitable companies and is better than other challenge submissions.

We are more than happy to answer any questions that you may have around the limitations of the challenge, but the XSSV partners are excited to see what creative solutions your team will submit.

Sincerely,
XSSV General Partners

Figure 2. *Example of a group case homework, where students need to pitch a chemical target that would utilize otherwise-wasted solar energy and sequester carbon dioxide.*

preliminary designs during a project check-in. Students then submit final reports that are typically 15-20 pages in length, figures and tables inclusive.

Full examples of all three types of cases, including teaching notes for the in-class case activities, can be obtained by contacting the corresponding author at chen.christopher@columbia.edu. Most in-class and group homework cases were reused each year with a few rotated in and out. The final case projects are not used for a few years after each run. Examples of student work on unused homework cases are given as examples to students to help them understand the deliverables for these homework assignments.

METHODS

To determine whether the addition of case-based learning affected the learning of students in the course, we are focusing our primary comparisons of student experience and learning between the Fall 2018 and Fall 2019 iterations of our MEB course. After Fall 2019 there were many other changes contextually (i.e., the COVID-19 pandemic) and pedagogically (i.e., flipping the course in response to remote teaching) that could have otherwise affected the student learning experience, as described in the Course Design section of this paper. For quantitative comparison we used the same first midterm (of two) and final exam questions (with modified numbers) for Fall 2018 and Fall 2019 and kept the questions on the course evaluations the same. We are mostly concerned in determining whether there was any negative impact on learning when replacing historical course elements (i.e., lecture, homework problems) with case-based activities and assignments in the first term of implementation.

As a means of understanding the impact of cases on student learning, we use a mix of qualitative (free response) and quantitative (Likert scale) data from more recent terms when use of cases in the course had matured (Fall 2021 and Fall 2022). We asked students to complete a survey separate from course evaluation, specifically asking about added course elements. This survey is appended to a required form that students complete to peer review their teammates' and their own contributions to the final project of the course, leading to high completion rates.

Free response answers to this survey were analyzed using standard approaches for developing emergent codes,[19] where the instructors read student comments and sorted them into themes that arose from the set. These themes were then iteratively combined, read for consistency, and adjusted to best fit student responses. Final coding placed comments into one or more appropriate themes. Using this approach, five categories appeared, including real-world applications, engineering thinking, and approaches to breaking down problems.

RESULTS AND DISCUSSION

Comparing Student Learning in Fall 2018 and Fall 2019

As MEB is the first technical course in the chemical engineering curriculum, students do not typically come in with background knowledge of the field. They do, however, tend to come in with a wide range of experience in STEM courses, with most sophomores having a year of college level courses, and the transferring juniors having approximately three years of experience. As a means of determining similarity between classes, we present the first midterm scores given five weeks into the course in Table 2. A comparison of these statistics suggests that the 2019 cohort of the MEB course may be slightly less experienced or prepared as compared to the 2018 class, due to the statistically significant difference between student midterm grades ($p\text{-value} < 0.01$) with a medium effect size difference (standard deviation-normalized difference in the means, with medium effect at $|d| = 0.5\text{-}0.8$) between the two midterm averages. Additionally, the inclusion of two case activities (two in-class case activities and one group case homework) that removed previous instructor-guided in-class problem-solving may have contributed to the lower scores in 2019.

However, student performance by the end of the course between 2018 and 2019 was similar on the final exam, as shown in Table 3. The apparent difference on the first midterm averages had disappeared by the end, with the difference between the exam scores between the two years being statistically significant ($p\text{-value} > 0.05$). We interpret these results to mean that the implementation of case studies in the course did not detract from student learning as measured in the exams, even though previous course elements had been removed (e.g., lecture time replaced by case activities

TABLE 2
Comparison of First Midterm Scores

	2018	*2019*
Mean	75.5%	66.8%
Median	80.0%	68.0%
Standard Deviation	15.6%	18.8%
Cohen's d*	-0.50 (medium effect size)	

*The difference between 2018 and 2019 was found to be statistically significant with a p-value < 0.05.

TABLE 3
Comparison of Final Exam Scores

	2018	*2019*
Mean	79.4%	80.2%
Median	80.3%	85.8%
Standard Deviation	17.2%	18.7%

and homework problems replaced by open-ended case responses) and greater emphasis was placed on non-traditional applications of chemical engineering approaches throughout the course.

Exam scores for 2020 and later are not presented here due to further changes to the course that may have more greatly affected student learning as measured by the exams.

Comparing Student Experience and Self-Reported Learning from Fall 2018 to Fall 2022

Student experience in the course was measured in part by the end-of-term course evaluations. We present student ratings across a variety of dimensions – appropriateness of the workload, perception of grading fairness, and course quality – in Table 4 for Fall 2018 to 2022, with the Cohen's d effect size only calculated between the 2018 and 2019 runs of the course, when the differences between the mean ratings were statistically significant (only in the case of grading fairness). Students self-reported amount learned did not have a statistically significant difference between the two years ($p > 0.05$), in line with the final exam data shown in Table 3. Given that students tend to have lower feelings of learning in active classrooms (more active learning in 2019) as compared to lecture-based classes (2018),[20] the finding that students had a similar rating of self-reported learning was positive.

However, students reported a significant difference with small effect size decrease ($|d| = 0.2\text{-}0.5$, $p < 0.05$) in grading fairness in the course. We were not surprised that the fairness of grading had decreased from 2018 to 2019, as more of the course grades became less strictly quantitative (e.g., problem sets) and more qualitative argumentation (e.g., case homework). Though also decreasing, the difference in the mean scores for course quality and appropriateness of workload were not significantly different ($p > 0.05$), though the drop in these scores were likely due to the same reasons as to why grading fairness had declined.

In the years following the introduction of case-based learning in the MEB course, student evaluations have generally improved (Table 4) despite teaching challenges during the COVID-19 pandemic. As mentioned previously, since 2020 our MEB class has been flipped, a pedagogical approach that students generally perceive as positive (though often mixed) on their learning experience – as compared to traditional classrooms – with anecdotal evidence of improved student learning.[21] This generally positive response by students is also seen in examples in chemical engineering, which also show similar or improved student learning with the shift to the flipped structure at the activity,[22] module,[23] and course level.[24, 25] Studies on the effects of flipping the MEB course have also been shared within the chemical engineering community with similar results – similar student learning and mixed-to-positive student response.[26] Unfortunately, we were not able to find others who had improvement in student experience survey questions similar enough to what we present in Table 4 to be able to separate the effects of flipping the classroom and the use of case-based learning for 2020-2022, though we believe that the positive results observed are due to both these pedagogical changes to the course.

The one exception to this was in 2021 when a prolonged graduate student instructor strike disrupted many undergraduate courses and likely led to the shown decrease in course evaluation – something that was common amongst many courses that term based on instructor discussions. This demonstrates that the implementation of case-based learning in the long term did not decrease the student experience and was likely a contributor towards its higher ratings.

As a note, the increased 2020 scores may also be seen as surprising given the general context of the pandemic and remote teaching during that term. We attribute this result in part due to the flipping of the course that occurred in that term in order to better adapt the class to the conditions during that particular term. As other courses our students had been taking may not have made the same adjustments

TABLE 4
Comparison of Likert Scale* Responses on Course Evaluation Student Experience Questions

Dimension	*2018 Mean*	*2019 Mean*	*2020 Mean*	*2021 Mean***	*2022 Mean*	*Cohen's d (2018 v 2019)*
Amount Learned	3.40	3.35	3.89	3.26	3.75	–†
Appropriateness of Workload	3.15	2.65	3.11	2.26	3.35	–†
Grading Fairness	3.65	3.18	4.11	2.74	3.85	-0.37‡
Course Quality	3.40	3.06	3.68	2.79	3.80	–†
Response Rate***	20 / 31	17 / 31	19 / 28	19 / 30	20 / 28	

*Students are asked to rate these course elements on a 1-5 scale, where 1 is poor and 5 is excellent.
**Fall 2021 data were affected by a graduate student instructor strike that disrupted a large portion of the term for undergraduate students and likely negatively affected student experience.
***Number of students responding to the course evaluations over number of students enrolled in the course.
†The differences between the 2018 and 2019 were not statistically significant ($p > 0.05$)
‡The difference in grading fairness between 2018 and 2019 was statistically significant ($p < 0.05$)

(which we had heard anecdotally from students), our course may have been found to be comparatively better, resulting in the improved survey responses.

Within the course evaluations, students were also asked to rate the extent to which the course contributed to their abilities as an engineer in relation to the student outcomes associated with ABET EAC Criterion 3 (Table 5). Here, between 2018 and 2019, we observe the largest mean self-reported differences in the decrease in student ability to problem solve and apply new knowledge, and increases in ethical responsibility and working on a team (all are not significantly different, with p-values of $p > 0.05$ for all three). The other three ABET EAC based student outcomes had no statistically significant difference in those two years ($p > 0.05$). However, in the years following the introduction of cases, increases across the seven student outcomes associated with ABET EAC Criterion 3 were observed compared to 2018 – with medium ($d = 0.5$-0.8) to large ($d > 0.8$) effect sizes and p-values less than 0.01. Data from 2021 were affected by the aforementioned campus context, but even in that term, self-reported learning towards these learning objectives was not statistically different form the 2018 run of the course. Again, we interpret these results to conclude that case-based learning did not diminish the student experience or learning in the course and was likely a contributor to these increases towards the student outcomes associated with ABET EAC Criterion 3.

Impact of Case-based Approaches on Student Learning

With the maturation of the use of cases in the MEB course, in Fall 2021 and 2022 we surveyed students to determine the value of various course elements in contributing to student learning toward the three course learning objectives (Table 1). In their self-reported confidence in the course learning objectives, students noted an average increase of 1.94 and 1.85 on a 1-5 scale between the beginning and end of the course in 2021 and 2022, respectively (Table 6).

TABLE 5
Comparison of Likert Scale* Responses to the Student Outcomes Associated with ABET EAC Criterion 3

ABET Student Outcome	*2018 Mean*	*2019 Mean*	*2020 Mean*	*2021 Mean**	*2022 Mean*
1. Problem- Solving	3.55	3.29	4.16	3.37	4.10
2. Engineering for People	3.40	3.29	3.89	3.32	3.90
3. Effectively Communicate	3.14	3.12	3.89	3.05	4.00
4. Ethical Responsibility	3.10	3.59	4.00	3.47	3.90
5. Working on a Team	3.45	3.76	4.32	3.42	4.25
6. Draw Conclusions	3.15	3.00	3.84	3.21	3.85
7. Apply New Knowledge	3.60	3.24	4.16	3.37	3.90
Response Rate**	20 / 31	17 / 31	19 / 28	19 / 30	20 / 28

*Students are asked to rate the degree to which the courses provided them the ability to perform the listed ABET learning outcomes on a 1-5 scale, where 1 is poor and 5 is excellent.
**Fall 2021 data were affected by a graduate student instructor strike that disrupted a large portion of the term for undergraduate students and likely negatively affected student experience.
***Number of students responding to the course evaluations over number of students enrolled in the course.

TABLE 6
Self-Reported Likert Scale* Confidence in Course Learning Objectives

	2021		*2022*	
*Course Learning Objective***	*Confidence at start of course*	*Confidence at end of course*	*Confidence at start of course*	*Confidence at end of course*
LO1. Explain Chemical Engineering Approaches	2.05	4.10	2.08	4.08
LO2. Propose Chemical Engineering Solutions	1.71	3.86	1.88	4.04
LO3. Critique Chemical Engineering Arguments	2.43	4.05	2.44	3.84
Response Rate***	21 / 30		25 / 28	

*Students are asked to rate their confidence in their abilities in the course learning objectives on a 1-5 scale, where 1 is no confidence and 5 is completely confident.
**Full course learning objectives shared with students can be found in Table 1.
***Number of students responding to the course evaluations over number of students enrolled in the course.

Since this change alone is not entirely due to the implementation of case-based approaches, we also asked how helpful each of the case elements was toward helping them build course skills, shown in Table 7. Here, students rate all three case activities as similarly helpful at a moderate extent (~3.5 out of 5), demonstrating that students recognize the benefit of cases to their learning. As a point of comparison, we also asked students to rate the helpfulness of traditional problem set homework, which was found to be more helpful to student learning (~4.5 out of 5). We suspect that the higher rating that problem sets received was partially due to familiarity with the format and its similarity with assessment on the final exam, which was the highest weighted part of the course grade (25%).

To dive more deeply into how the case-based activities helped student learning, students were asked to share how the cases (in-class, homework, and project) helped their learning. Through review of the responses, five major themes emerged that are listed in order of frequency in Table 8. The most frequent was the theme of real-world applications (61% of responses), where students noted how cases helped to demonstrate the roles of chemical engineering in practice or connected into problems they could encounter. An example of a comment that would be coded as real-world applications is:

> *The projects and case studies showed me how chemical engineers can solve problems in many different industries from the example that was given about making sausage to building a moon base.*

The second most frequent was the theme of thinking like an engineer (39% of responses). This theme included responses that referred to how engineering problem-solving was not black and white, the dependency of proposed solutions on assumptions and context, and the complexity of data that needed to be considered in the crafting of an engineering solution. This is an important connection as we believe the transferable skills we want to facilitate are included in general engineering thinking. An example of this category is found in the following statement:

> *The project informed me about how assumptions play a huge role as a chemical engineer. Of course, there is a lot of information out there but knowing what to choose and ignore is extremely important to succeed.*

Breaking down problems was the third most common theme (35%), which includes references to tackling larger challenges in smaller parts and using some process to subdivide complex problems. This often overlapped with the least mentioned theme of teamwork (11%). Both of these themes can be found in the following student response:

> *I think having the full memo of what was needed was helpful because it allowed me to explore different ideas and possibilities for questions I needed to address. I also think that within our groups or engineering groups in general, it became apparent that different individuals within a group can have different strengths and weaknesses.*

Reinforcement of class concepts (24%) was assigned to comments that saw case activities as a way to hone course skills. This category had some overlap with the real-world applications theme but may also include responses that do not specify to what problems or contexts course concepts could be applied. For instance, the following quote would be categorized as both reinforcement of class concepts and real-world application:

> *The final project definitely helped me put into perspective what a chemical engineer does. Specifically, comparing it to the case studies we did in class where we would analyze a person's approach to a process. I was able to visualize and explore how various concepts from the class interconnect to give a good analysis.*

TABLE 7

Student Likert Scale* Ratings of Helpfulness of Case-Based Course Elements

Course Element	*2021 Mean*	*2022 Mean*
In-Class Case Activities	3.51	3.59
Team Case Homework	3.51	3.85
Final Project Case	3.69	3.35
Problem Set Homework	4.23	4.85
Response Rate**	21 / 30	25 / 28

*Students are asked to rate these course elements on a 1-5 scale of helpfulness, where 1 is not very, and 5 is very helpful.
**Number of students responding to the course evaluations over number of students enrolled in the course.

TABLE 8

Frequency of Themes in Student Responses to How Cases Helped Their Learning

Theme	*2021*	*2022*	*Total Frequency*(%)*
Real-World Applications	14	14	61%
Thinking Like an Engineer	10	8	39%
Breaking Down Problems	7	9	35%
Reinforcement of Class Concepts	6	5	24%
Teamwork	1	4	11%
Total Responses	21	25	

*Total frequency of the theme in both years divided by the total number of responses (46).

In contrast, the following comment would be coded as reinforcement of class concepts, teamwork, and breaking down problems but not real-world applications:

> *The project helped me learn how to work with other teammates in order to fulfill a long project. The case studies helped me understand the calculations and thought process of chemical engineers.*

Student responses to how cases helped them learn in the course align with our goals for case implementation: to help students see how they can apply chemical engineering approaches inside and outside of a traditional chemical engineering context to make decisions. Given that student responses included real-world applications far more frequently than reinforcing course concepts, we interpret this as students seeing the usefulness of these approaches beyond the classroom. Additionally, we were heartened that engineering thinking appeared in 39% of responses (second most frequent) as a demonstration of student understanding that calculations alone were not enough. Instead, students understood that interpreting and drawing conclusions from data in context are important for engineering decision making.

Addressing Diversity, Equity, and Inclusion

Case-based teaching is already seen as a pedagogy that can be inclusive when done well due to its storytelling nature [19] and has been shown to be helpful in increasing inclusivity in chemical engineering.[8] Using our definition for inclusive teaching as learning activities that are meaningful, relevant, and accessible to all,[27] our cases are designed to help students see themselves as chemical engineers through multiple approaches. First is through the characters that the students encounter within the cases themselves. Care was taken to diversify the genders, names, and roles of the actors in the stories so that students could experience some of the diversity present in the practice of engineering. This was also done in the hope of making the field appear more accessible to students by allowing them to see themselves in the presented cases. We will note that these are not features of the cases that are included in Felder and Rousseau's cases in *Elementary Principles of Chemical Processes*.[14]

Second is in how we ask students to bring themselves into the engineering decision- making within each case. Although we expect students to be able to reach the same quantitative answers, we do not expect, and in fact encourage, students to disagree with each other in the interpretation of these numbers. We work, as instructors, to help guide students toward understanding why they may interpret numbers differently based on their own experiences and to see the integration of their personhood into their decision-making as a meaningful important part of their development as engineers. Students are also encouraged to take on different viewpoints through the characters presented in the case and through the discussion of potential solutions to help our students practice empathy in their engineering problem-solving.

Finally, we have worked to develop cases based on topics in current events and popular media to make them more relevant to students. This is most seen in the longer case forms (group case homework and final project case). These more open-ended projects also allow students a chance to explore topics of their own interest (as seen in the excess solar challenge example in Figure 2) to motivate their learning while still honing the course skills for the exercise (in this example, the ability to conduct atom and process economy calculations, and to research the production scales and size of the demand for chemical products).

Given that the addition of case-based activities could have easily required more time for students to prepare for the course, we tried to balance our additions with reductions in other activities to prevent a much greater-than-historical class workload. As students have many other challenges and responsibilities outside of our course, we found that balancing our approach in the course redesign to teach with cases was an important accessibility issue for students that needed to be considered. As discussed earlier on, we found that the removal of these previous course elements did not seem to reduce student learning in our course.

CONCLUSION

We introduced cases in our MEB course to help encourage our students to not only consider the quantitative answers to problems but also see how to make decisions from those calculations. This was done at three different scales: in-class case activities, which displaced lecture time; team case homework, which displaced traditional quantitative homework problems; and a month-long team-based final case project. (Examples of each of the types of cases can be obtained by contacting the corresponding author at chen.christopher@columbia.edu.)

When implementing cases for the first time in the class, we demonstrated that students still made progress towards the learning objectives for our MEB course (Table 1) through similar final exam (Table 3), in similar self-reported learning ratings (Table 4), and progress towards student outcomes associated with ABET EAC Criterion 3 (Table 5) in the Fall 2018 and Fall 2019 iterations of the course. Given that previous course elements needed to be removed to make class time for case activities, we found that similar results across many of these measures of student learning was an important indicator that introducing cases was not negatively affecting student learning. Certain dimensions of student experiences were negatively affected between the 2018 and 2019 iterations of the course (with the decrease perception of grading fairness being statistically significant, $p < 0.05$), which may be related to the shift from mostly quantitative assignments towards problems that do not have a clear correct answer in the cases.

Since the introduction of cases to the course in 2019, however, student ratings in course evaluations (Table 4) and self-reported progress on student outcomes associated with ABET EAC Criterion 3 (Table 5) have generally increased since that term, despite the challenges of the COVID pandemic. We attribute this increase in part to the shift toward case-based instruction that was a continuous part of the course despite other changes in format necessary for engaging students remotely and in a hybrid environment. We recently have evaluated the helpfulness of case-based learning on self-reported student learning toward the course learning objectives in the Fall 2021 and 2022 iterations of the course (Table 7). Students rated all three types of case activities as moderately helpful to their learning (~3.5 out of 5, where 1 is not very helpful and 5 is very helpful), though these course elements were rated less helpful than traditional, problem set homework (~4.5 out of 5) for their learning.

We coded student responses to how cases helped their learning in the course to better understand the student experience with case-based activities. The five most prevalent themes (Table 8) were seeing the real-world applications of chemical engineering (69% of 46 responses), thinking like an engineer (39%), learning how to break down complex problems (35%), reinforcing course skills (24%), and working on a team (11%). Given that our goal for introducing cases was to help students see chemical engineering skills in a broader context of applications, roles, and decision-making, we found this breakdown of student responses in alignment with our aims. Generally, we found it heartening that students themselves recognized the usefulness of the case exercises for their learning.

We hope our examples help encourage other chemical engineering educators to try case-based instruction and inspire them to write new cases that better motivate and engage their students. Beyond this project, we plan to continue to explore and measure the effects of case-based methods on student learning in other contexts within chemical engineering.

REFERENCES

1. Varma A and Grossmann IE (2014) Evolving trends in chemical engineering education. *AIChE Journal*. 60(11):3692-3700. DOI: https://doi.org/10.1002/aic.14613.
2. Godwin A and Boudouris BW (2020) Fostering motivation for chemical engineering students' academic success: An example from a sophomore materials and energy balances course. *Chem Eng Ed*. 54(3):121-128.
3. Zydney AL (2021) Keeping chemical engineering education relevant. *AIChE Journal*. 67(4):e17203. DOI: 10.1002/aic.17203.
4. Gillett JE (2001) Chemical engineering education in the next century. *Chemical Engineering & Technology*. 24(6):561-570. DOI: https://doi.org/10.1002/1521-4125(200106)24:6%3C561::AID-CEAT561%3E3.0.CO;2-X.
5. Felder RM, Brent R, and Prince MJ (2011) Engineering instructional development: programs, best practices, and recommendations. *Journal of Engineering Education*. 100(1):89-122. DOI: https://doi.org/10.1002/j.2168-9830.2011.tb00005.x.
6. Herreid CF (1997) What makes a good case. *Journal of College Science Teaching*. 27(3).
7. Prince M (2004) Does active learning work? A review of the research. *Journal of Engineering Education*. 93(3):223-231. DOI: 10.1002/j.2168-9830.2004.tb00809.x
8. Koretsky M, Montfort D, Nolen SB, Bothwell M, Davis S, and Sweeney J (2018) Towards a stronger covalent bond: Pedagogical change for inclusivity and equity. *Chem Eng Ed* 52(2):117-127.
9. Herreid CF (1994) Case studies in science - A novel method of science education. *Journal of College Science Teaching*. 23:221-221.
10. National Center for Case Study Teaching in Science Case Collection (2022) https://www.nsta.org/case-studies. accessed on Aug. 4, 2023.
11. AIChE Concept Warehouse. https://conceptwarehouse.tufts.edu/cw/. accessed September 4. 2023
12. LearnChemE. https://learncheme.com accessed September 4. 2023
13. Fedesco HN, Kentner A, and Natt J (2017) The effect of relevance strategies on student perceptions of introductory courses. *Communication Education*. 66(2):196-209. DOI:
14. Felder RM and Rousseau R (2005) *Elementary Principles of Chemical Processes*. John Wiley & Sons, New York, NY.
15. Felder RM, Rousseau RW, and Bullard LG (2020) *Elementary principles of chemical processes*. John Wiley & Sons, Hoboken, NJ.
16. Chen C. (2022) Redesigning to foster community in an online iIntroductory chemical engineering course. *Proceedings ASEE Annual Conference*. https://peer.asee.org/41889.
17. Peters A (2021) This startup keeps CO2 out of the air by injecting 'bio oil' underground. *Fast Company*. https://www.fastcompany.com/90677039/this-startup-keeps-co2-out-of-the-air-by-injecting-bio-oil-underground accessed August 4, 2023.
18. Weir A (2017) *Artemis*. Ballantine Books, New York, NY.
19. Creswell JW and Creswell JD (2017) *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. SAGE Publications, Thousand Oaks, CA.
20. Deslauriers L, McCarty LS, Miller K, Callaghan K, and Kestin G (2019) Measuring actual learning versus feeling of learning in response to being actively engaged in the classroom. *Proceedings of the National Academy of Sciences*. 116(39):19251-19257. DOI: 10.1073/pnas.1821936116.
21. Bishop J and Verleger MA (2013) The flipped classroom: A survey of the research, *Proceedings 2013 ASEE Annual Conference* . DOI: 10.18260/1-2--22585.
22. Koretsky M, Mihelic SA, Prince MJ, Vigeant MA, and Nottis KE (2015) Comparing pedagogical strategies for inquiry-based learning tasks in a flipped classroom, *Proceedings 2015 ASEE Annual Conference and Exposition, Seattle, Washington*. DOI: 10.18260/p.23714.
23. Cheah S-M, Lee H-B, and Sale D (2016) Flipping a Chemical Engineering Module using an Evidence-based Teaching Approach, *Proceedings Proc. of the 12th International CDIO Conference*. http://www.cdio.org/knowledge-library/documents/flipping-chemical-engineering-module-using-evidence-based-teaching.
24. Cheah S-M and Sale D (2017) Pedagogy for Evidence-based Flipped Classroom–Part 3: Evaluation, *Proceedings Proc. of the 13th International CDIO Conference*. http://www.cdio.org/knowledge-library/documents/pedagogy-evidence-based-flipped-classroom-part-3-evaluation.
25. Fauteux-Lefebvre C (2019) The Impact of the Classroom Environment on the Transition from the Traditional Model to the Flipped Classroom in a Unit Operation Course. *Proceedings of the Canadian Engineering Education Association (CEEA)*. DOI: 10.24908/pceea.vi0.13754
26. Lai VK (2020) Flipping the Classroom for a Material and Energy Balances Course: Effect on Student Learning versus Student Perception and Sentiment. *Chem Eng Ed* 54(3):160-170.
27. Mirakhur Z, Chen C, and Schwarz S (2022) A case study in teaching inclusive teaching. *To Improve the Academy: A Journal of Educational Development*. 41(2): 1. DOI: 10.3998/tia.386 ❑