Techno-economic Modeling as an Inquiry-based Design Activity in a Core Chemical Engineering Course

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Abstract

Purpose. Authentic engineering practice is often introduced to students through engineering problem-solving in the classroom. These problems usually have a single, correct answer and fail to guide students' problem framing against real-world parameters and constraints. In this paper, we present techno-economic modeling as a computer-based pedagogical tool in a sophomore chemical engineering course to connect students' collective inquiry activities to real-world consequences.

Methodology. We conducted a study to illustrate how a techno-economic modeling tool can be used to enhance engineering reasoning within a collaborative environment. We aimed to answer the following research question:

- How might techno-economic modeling enhance students' ability to empathize with the communities for which they design and support students to make informed design decisions?

An algae biofuel design challenge was embedded into the sophomore material and energy balances course (n=56 in 10 teams) at a Hispanic-serving research university in the Southwest US. Wikis were used as a supporting collaborative tool for students to visually and textually report their knowledge and decisions on the three phases (growth of algal species, harvesting algae from water and extraction of oil from algae) of the challenge. Each team was assigned to investigate the economic feasibility of algal biofuel plant in a specific county. An open coding scheme was developed and used to analyze each teams' work on the economic feasibility of the algae biofuel plant.

Results and Implications. Analyses revealed that all student teams investigated the effect of constraints, such as population size and resource availability on design parameters like the choice of carbon dioxide source and biofuel production rate. Teams used cost and environmental impact as critical decision criteria to make informed decisions about the various process technologies. Additionally, we found teams to be attentive to decisions that could adversely affect a community. We found that economic modeling supported the students to engage in design decision-making akin to the professional practices of real-life engineers.

Introduction & research purpose

Broadly, sustainability is a key consideration in engineering design, and researchers have argued that it should be the context for all engineering work [1]. One common approach to teaching sustainability is through cases that are carefully prepared for students, helping to make key points salient [2]. However, encouraging students to consider complex issues, including stakeholder needs, contextual constraints, economic feasibility, and environmental impacts in an integrated fashion may best be done through a design challenge. Yet, because these are complex and often interrelated, students may struggle to make decisions. The purpose of this study was to investigate how scaffolding might support sophomore design teams to use techno-economic modeling to guide their design decisions related to an algae biofuel plant design for a rural Southwestern US community.

Background

We situate our study as constructionist [3], meaning we view learning as best supported when students work on a task that is meaningful to them, constructing their understanding by working on projects that have meaning beyond the classroom. While many design challenges might be considered constructionist, we emphasize ways to make meaningful engagement feasible for faculty to manage.

Scaffolding design learning

Design problems are termed *ill-structured* because they have many possible solutions, rather than a single correct answer [4]. Because students predominantly experience well-structured problems, they often struggle with design problems. To aid them, instructors can scaffold their learning by providing tools and supports that help them perform in more expert ways as they learn.

Design projects in engineering comprise complex tasks and implementation of these projects in the classroom can prove challenging as instructors try to simultaneously achieve conceptual learning outcomes. Students benefit from instructors who scaffold inquiry-based learning to manage and promote the skills needed within the complex task. The use of software as a scaffold with controlled parameter input supports the learning process for students and is less overwhelming [5] but may not enhance creativity. Thus, we based our use of a software scaffold on manipulated parameter input to assist in the diversification of student design solutions. Additionally, we leverage problematizing, where students are confronted with complexity but care enough to understand the issues [6] by using contextual design statements. The use of scaffolds including software have the potential to place students on a higher performance level and can lead to fading or scaffolded achievement [7].

Recent research raises concerns about over-scaffolding learners; while they sometimes perform better on short-term knowledge gains than peers who are not scaffolded, they also reportedly develop negative attitudes toward the subject matter [8]. Instead, providing goals, such as a design challenge, can better organize their learning. Other forms of scaffolds can also provide benefit. For instance, scaffolds that organize student work on ill-structured problems can support them to think about the problem and learn as they do so [9].

The design process spans definition of problem, navigation of the scientific literature for background, brainstorming multiple solutions, evaluating the solutions for the best solution, possible re-design and concluding on the design. Students are faced with regulating their efforts in designing a solution individually [10] and together as a team [11]. We use techno-economic modeling as a tool to help students navigate complexity in the uncertainty and multiple process parameters present in the project to engage them in the practice of real-life engineers [12]. Writing can play an important role in helping students understand that many problems they face lack a single correct solution and benefit from iterative refinement [13].

Scaffolding writing

Increasingly, the communications we engage with are multimodal [14]–[17], meaning they are composed of text, images, and even audio or video clips. This is also true in technical writing, where students must interpret figures and tables—and in some cases video or .gif depictions of such as processes or reactions—for the reader. This is a complex and difficult process to learn to do effectively [18]. Helping students learn to compose in this manner can support them to communicate clearly.

One challenge with much of academic writing is that in lieu of an authentic audience, students are accustomed to writing for their instructor. Because they know the instructor already knows much about the subject, the task of writing, instead of fundamentally being about communication, can become little more than busy work, viewed as an inefficient means to convey the accuracy of one's ideas [19]. Thus, because of our constructionist approach, we prioritized the idea of audience. Others have suggested that writing for popular and non-technical audiences can help students develop their communication skills [15]. Even when writing for a technical audience, having a sense of that audience can help students be clear about terms that even a technical audience may not be familiar with, thus improving the clarity of writing [13], [20]. We therefore decided to have students write blogposts aimed at an educated but not expert audience. Even when writing in forms atypical for engineers there is value for students, as they can learn more about the concepts through writing [21]

Methodology

This study reports on the third iteration of a longer-term design-based research (DBR) study [22], [23]. DBR is a method that allows researchers to test their hypotheses about how learning can be supported by conducting iterative cycles of classroom-based study. In this method, the course instructor typically collaborates with a learning scientist to document and analyze the impact of carefully planned instruction. Each cycle provides an opportunity to evaluate how the instruction did or did not support learning as intended. This study, therefore, builds on findings from the previous two iterations.

Participants & setting

The participants included 56 students in 10 teams enrolled in a sophomore-level materials and energy balances course, a core course in the chemical engineering program at a Hispanic-serving research university. Students worked in teams of seven to eight students. Each team included students who *specialized* in one of the production phases: growth, harvest, or extraction. By this, we mean that they were tasked with considering each design decision from their particular specialization, including as they conducted research. In related work, we have found that they commonly made reference to their specializations during team discussions.

Materials and data collection

Data were collected during the third iteration of the course after redesigning it as part of an NSF project. Specifically, we threaded a design challenge focused on the conceptual design of an algal biofuel plant through the course. Elsewhere, we discuss specifics related to how we revised each homework to align to the course content, enhancing but not replacing it and how we supported students to work in teams and productively learn from one another [24]–[26].

In this iteration, we added scaffolds for techno-economic modeling and blogging. These included an Excel spreadsheet that was designed to support students to navigate modeling, and wiki posts that supported them to evaluate possible options related to growth, harvest and extraction.

Techno-economic modeling uses multiple techniques that calculate and manipulate process parameters to make predictions about costs and profitability. A process model for the algal oil production was developed using Aspen Plus™ to simulate different algal oil production rates.

Each team was assigned a New Mexico community and given information about wastewater and carbon dioxide emission sources specific to each community. Students input process parameters, including water, urea and carbon dioxide feed rates into Aspen Plus™ . Additionally, students input the oil content for their respective algal species. The results reported from Aspen Plus™ included mass flow rates for dried algal mass and algal oil. The processing of algal oil to biodiesel was not included in the model, but a simple percent conversion assumption was used to calculate the biodiesel output. The results from Aspen Plus™ were then input into Microsoft® Excel®. Students used it along with Aspen Plus™ to evaluate the energy costs of the different production phases (growth, harvest and extraction). For example, in the growth phase, students evaluated the energy costs associated with pumping water for cooling, the growth medium and culture.

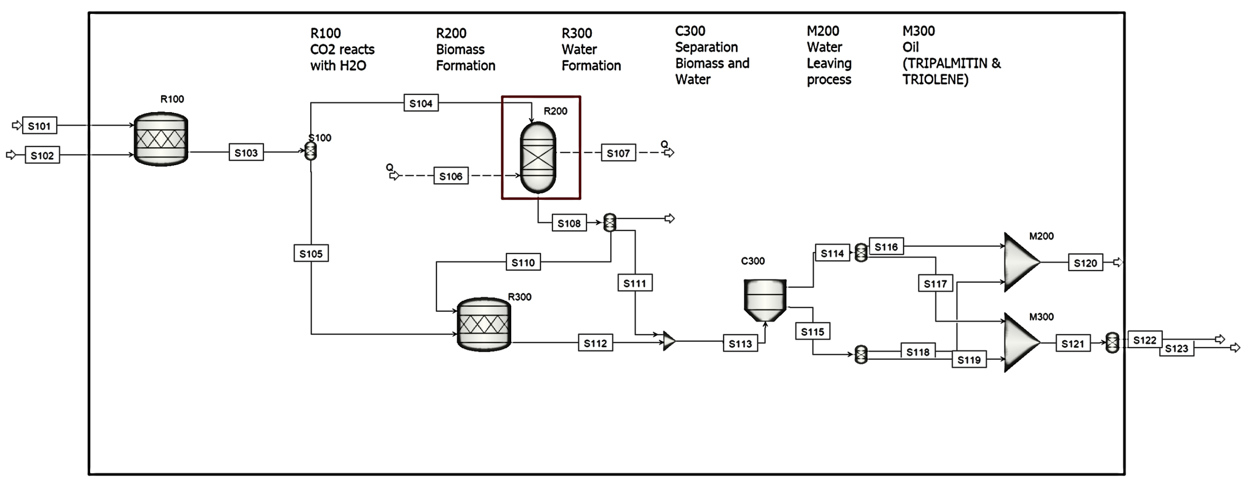

Figure 1. Aspen Plus™ process model for growth of algae, harvest from water and extraction of algal oil. The process steps for conversion of algal oil to biofuel is not shown.

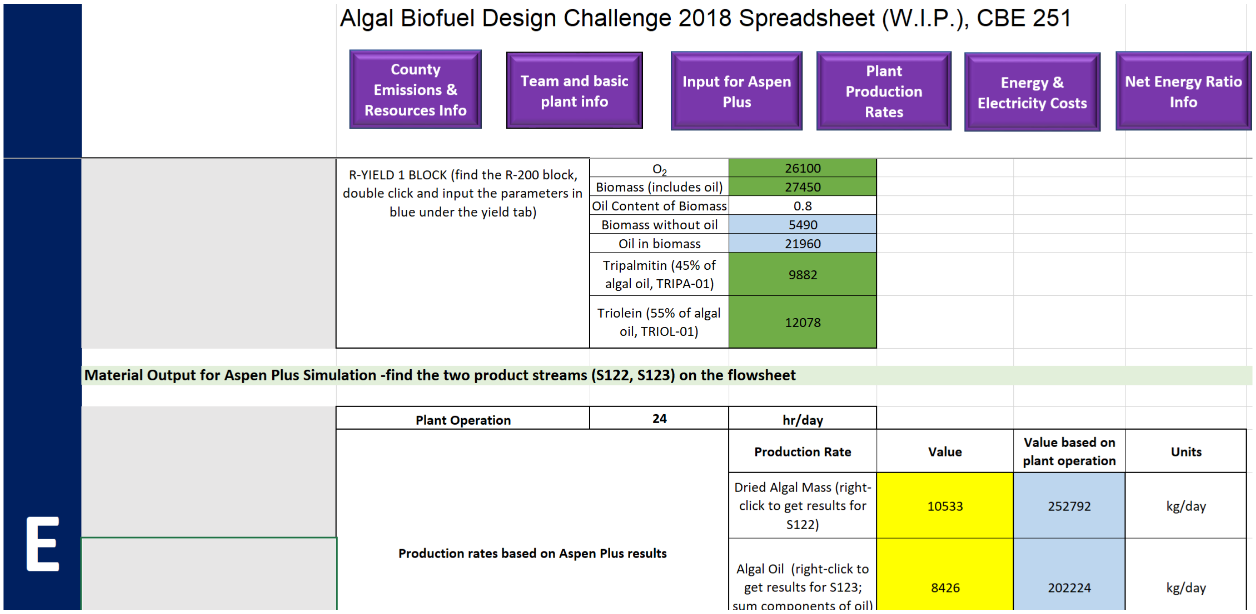

Figure 2. Microsoft® Excel® spreadsheet calculations for energy costs associated with growth of algae, harvest from water and extraction of algal oil for different production rates which varied by community.

In the first wiki post, students were instructed to explore sources of carbon dioxide and water to grow algae in a specific New Mexico community. The second wiki post asked them to explore methods of harvesting algae, and the third on methods of extracting oil form the algae. Although they were prompted to refer to the techno-economic modeling in all wikis, they drew upon these only in the third wiki. For all wiki posts, they were instructed to detail the benefits and drawbacks of each option and include supporting research notes/media with necessary citations. The wikis were completed using the wiki tool in the Blackboard Learn system.

Students used their wikis and modeling to develop multimodal blogposts. Instead of reviewing the benefits and drawbacks of various solutions, they were tasked with writing persuasively about their choices for the algal strain, open pond or bioreactor and other growth-related details, and mechanisms for harvest and extraction.

Data collection & analysis

We conducted qualitative analysis of student work on the wikis [27]. This approach is similar to grading with a rubric (Table 1). In this case, we first reviewed the student work to identify common themes that related to our research focus. In this case, we particularly attended to comments that indicated students had investigated specific resources in the local communities they were designing for, that they evaluated possible solutions in light of pros and cons, and the degree to which they articulated tradeoffs and the complexity of processing (e.g., that carbon dioxide may not be readily available in a usable form).

Table 1. Coding scheme for growth, harvest, and extraction wikis. Each wiki was assigned a score of 1 if the code was present and a score of 0 if it was not.

Code	***Description***
Specific name	Provides specific name of farm, dairy, other resource that is locally available
Specific details	Provides specific details of local resource that is locally available
Pros	Clear explanation that a resource meets their needs or is a positive, connected back to problem
Cons	Clear explanation that a resource fails to meet their needs or creates additional steps/costs, connected back to problem
Tradeoffs	Any mention of a tension between two desirable options or endpoints (e.g., environment versus economics)
Processing	Explanation that processing is needed, recognition even if they don't know specifics

To assess the degree to which teams were empathetic in their design decisions, we specifically consider three of these codes, specific details, pros, and cons. For analytic purposes, we operationalize empathy as considering specific details of the community and explaining how a resource or method meets and fails to meet the community needs. We examined the co-occurrence of these three codes for each wiki by team.

The final blog posts were assessed using a rubric (Table 2).

Table 2. Coding rubric for final blogs

	Near expert	Competent	Novice
Expertise	*20 points* Research conducted this semester is consolidated effectively to persuade your stance on algal biofuel technology to the reader.	*15 points*	*10 points* Needs major revisions.
Evidence	*20 points* Research is well consolidated to effectively prove your stance on algal biofuel technology to the reader.	*15 points*	*10 points* Needs major revisions.

Originality	*15 points* The blog offers a unique argument or insight based on your community and the inquiry learning tools	*10 points*	*5 points* Needs major revisions.
Usefulness	*15 points* The reader can easily understand the block flow diagram and how the different unit operations fit together for each stage. Inputs and outputs for materials and energy in the	*10 points*	*5 points* Needs major revisions.
Persuasion	*15 points* The article is a pleasure to read as well as informative. Multimodal (images, video, drawings) communicate the writers' thoughts and provoke interest. The story about implementing algal biofuel technology in the assigned	*10 points*	*5 points* Needs major revisions.
Multimodal Story-telling	*15 points* The need or problem addressed in your article is effectively communicated through careful selection and placement of multimodal elements. The narrative uses images to economize text effectively to help the reader	*10 points*	*5 points* Needs major revisions.

Results & discussion

Design decision-making

We found that students named specific local resources only in their wiki posts about growth (Figure 1). For instance, one team explained, "This refinery is called Navajo refinery. We could work with the refinery to capture the carbon dioxide and use this to supply the the *[sic]* CO2 that is needed for the algae to grow. This would be beneficial to both us and the refinery because they would be polluting the environment less and we would be getting CO2 for our algae."

They included specific local details in the growth and extraction wikis, but not in the harvest wiki. The kinds of details they included were tied to both the phase and to the instructional tasks. For instance, in the growth phase, many students noted specific names and details of natural and agricultural features, as well as plants that might be sources of carbon dioxide in the counties they were designing for; for example, teams described:

- "Zia II plant in lea county, New Mexico" which "has a capacity of more than 1.3 Bcf/d and produces in excess of 130,000 barrels per day of natural gas."
- "the Pecos River which flows to the towns eastern border" cited as a source of water for their project
- One team provided an evocative description of a resource in their county, "Eddy county is most recognizably home to Carlsbad and its world renowned super caverns. However, when it comes to the cultivation of algae one could not be more excited than to the city just north of the latter. Artesia New Mexico contains the Navajo Refinery operated by the HollyFrontier Cooperation, a collection and processing facility for a multitude of crude oil types."

- "In the county of Curry, New Mexico, which is part of Clovis, farming and agriculture is a stability factor in the economy. With an estimated 17.5 inches of rainfall a year compared to a 14.2 inch statewide average, Curry county has the potential to have more access to water for growing algae in the first place"
- "and given the right conditions which in the county of Eddy during the summer wouldn't be a big problem since it almost always is above 20 C"

One team that referenced specific contextual information in their evaluation of an extraction method explained "Fortunately, New Mexico, more generally Lea county, can see nearly 280 sunny days a year making the oil expeller a successful extraction method for algae biofuel." More commonly, students referenced the specific numbers they input into their models. These numbers were county-specific; some were provided by the instructor and others were calculated by the teams. This was prompted by the instructional task, as students were required to use the techno-economic modeling tools at this phase:

- "The simulation was run at 25 degrees C, which is close to the average temperatures in the spring, summer, and fall when we would be growing the algae."

In all phases, students referenced the pros of the options they were considering (Figure 3). They almost always also included cons, though these were not always as detailed. For instance, one team, considering methods of harvest, explained "[Pro:] With this technology, Origin also promised that they can remove harmful, unwanted microbial in the product such as ciliates or parasites. With this promise, we can eliminate one of the biggest problems of open pond farm…[Con:] The system could be costly as they are pending the patent." Likewise, in the extraction wiki, a team noted "Even though the supercritical can be environmentally better and safer for production workers. It is very expensive, has a high power consumption"

In considering pros and cons, particularly as they began exploring harvest and extraction methods, many students considered these as tradeoffs. For instance, in the harvest wiki, teams explained:

- "The difference between these two options is price and effectively. The clarifier is more expensive but overall more effective then the settling basin. The settling basin is far cheaper in the short run but is less effective then the clarifier. The difference in costs and efficiency are both important factors in our harvesting process that will have to be considered."
- "We finally can also use the water after separation. But it does comes with problems such as constantly watching the machine while its working. It can have a capacity limit, which can also cause cell damage to dry algae mass product. The other issues can be the cost of electricity and motor damage."

In the extraction wiki, they also considered tradeoffs:

- "a quicker extraction time but with this comes the draw back of requiring quite a bit of energy"
- "This method overall is very effective but comes at a safety risk and a large cost."

- "This method is very quick taking approximately 10 minutes per batch but yields only around 52% of the oil recovered "

In terms of processing, some teams noted that carbon dioxide and water sources would need some form of treatment, though they did not provide specifics about the treatment process needed. In contrast, in the harvest and extraction wikis, which were more technically-oriented, teams provided detailed and warranted accounts of the processing required, and they commonly noted how these related to environmental and financial costs.

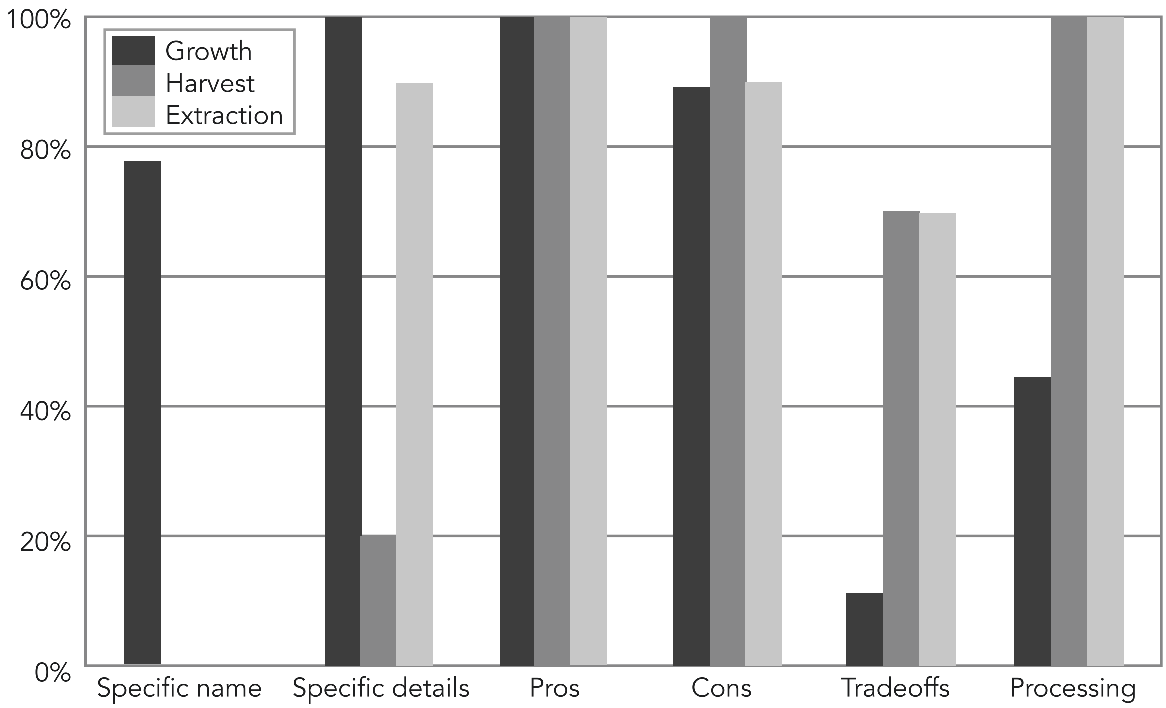

Figure 3. Average scores on all codes across the three wiki posts for growth, harvest, and extraction.

We found that all teams displayed empathetic reasoning on at least one wiki. Most teams considered specific details of their communities along with pros and cons, particularly when considering growth and extraction, though few did so when considering harvest (Figure 4).

For instance, in considering sources of water, possible strains, and ways to grow algae, one team explained, " Bernalillo county has limited water resources available that we would be able to use, without impacting the local agriculture industry." Another noted " The natural resource, the Pecos river, can be used for water and cooling sources. Eddy County is also home to the Navajo Fuel Refinery in Artesia. The crude oil operation there could be utilized for its CO2 exhaustion as a necessary resource for algae growth." Both of these comments consider the community needs as they weigh many design decisions related to algal biofuel production.

Some teams provided detailed reasoning about how or why certain strains or approaches to growing might or might not work in their assigned community:

- "Luna county is famous for its farmland and livestock which is crucial for Algae growth. Most of our water input comes from dairy farms in the region. Unfortunately, the problem that arises in any algae system in Luna county is a lack of CO2 reserves. One source of CO2 that is typically utilized is coal mines, however there are not any coal mines in Luna county that can be used as a source of CO2"
- "Roosevelt County, New Mexico, has an economy revolving around agriculture, specifically cattle rearing, which produces nitrogen rich wastewater. The ability to grow in wastewater heavily influenced our decision to use Chlorella because it allows us to use farm runoff water, an abundant resource in Roosevelt."
- "As mentioned previously, we want to be environmentally conscious and reuse as many sources as we possibly can. The great thing about New Mexico is the availability of land that is not currently being used for a source of agriculture. In Socorro, New Mexico the source of fossil fuels is decreasing. Producing algal biofuels in Socorro will simultaneously solve all these issues. Algal Biofuels provides an economic alternative to conventional biofuels while also improving Socorro's environmental sustainability. Socorro also has mines that will be a great source of CO2 for our algal growth process."

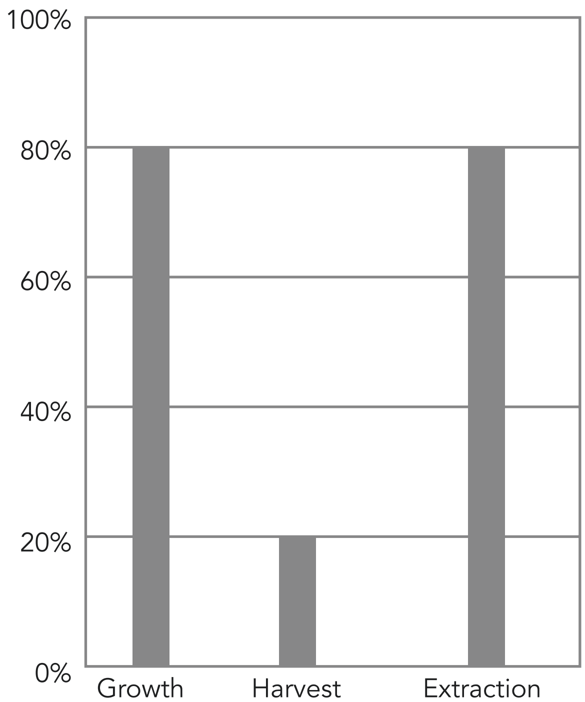

Figure 4. Empathetic reasoning on the wikis related to growth, harvest, and extraction

Blog posts supported authentic engagement

We assessed student teams' final work on the blog post using a rubric that emphasized both accurate content knowledge and writing conventions and style (Figure 5). We found the rubric breakdown by six criteria to be helpful in grading the student blogs and saved the instructor time. The criteria complemented course learning objectives including drawing process flowcharts from process descriptions. The first criterion was expertise based on students' ability to effectively consolidate a large amount of research to persuade the audience stance on the process for algal biofuel technology. The next two criteria were evidence to prove stance using the inquiry learning tools provided and originality to situate the audience in a local New Mexico community. The other criterion is usefulness for students' ability to depict information by way of a block flow diagram. The last two criteria focused on multimodality to support persuasion and the narrative. Student teams were able to meet most of the criteria on the proficient level and higher with the exception of originality. The instructor found that teams reported the results for the process calculations executed in Microsoft® Excel® and Aspen Plus™ but did not effectively weave the knowledge gained into the blog to strengthen their design arguments. The rubric utilization allowed the instructor to identify learning targets that need further emphasis such as algal productivity and oil content. Students completed research on these algae characteristics in the first design activity, parley one, but omitted these findings in the blog article.

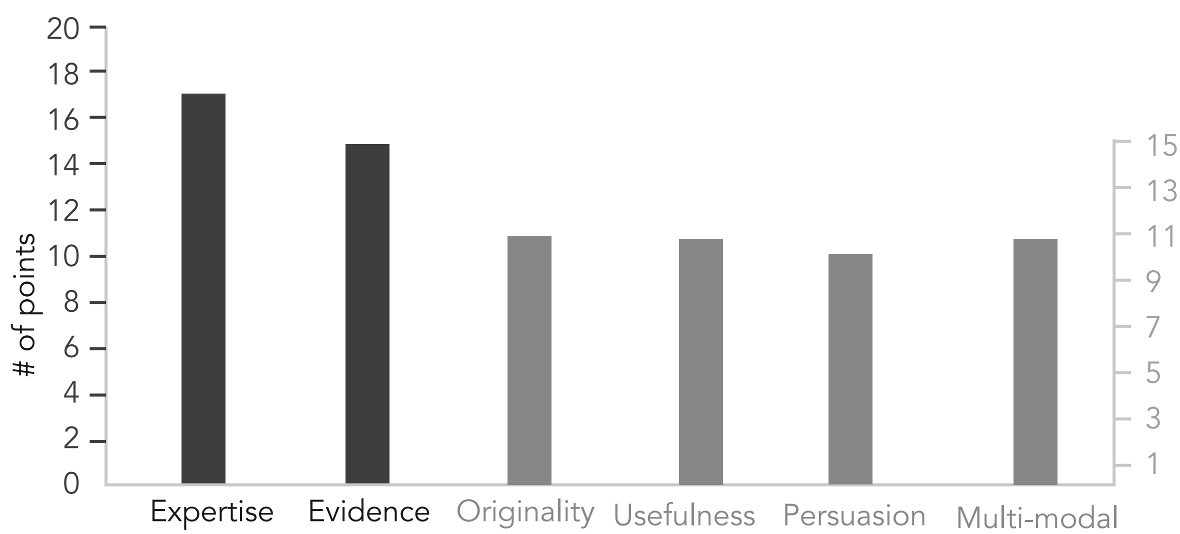

Figure 5. Average scores on rubric categories.

Conclusions, limitations, and implications

We sought to investigate how techno-economic modeling can enhance students' ability to empathize with the communities for which they design and support students to make informed design decisions. We found that incorporating scaffolds for techno-economic modeling supported sophomore students to conduct sophisticated analysis and make design decisions that were informed by research and empathetic to community needs.

We acknowledge the limitations presented by our study design. While this paper reports on the third cycle in a design-based research project, the past cohorts are not appropriate for comparison because the assignments differed, related to techno-economic modeling. Therefore, future research will make comparisons to better establish the impact of our approach.

We also note that we did not assess student perceptions of techno-economic modeling. Research suggests that student perceptions are not reliable indicators of whether an intervention supports learning [28]. However, we do note that students engaged deeply with the assignments, which suggests that students found them valuable. However, future studies can investigate specific aspects students found worthy to invest time. As a fairly authentic task, exploring how techno-economic modeling might support professional identity development would be of interest.

We conclude with implications for other chemical engineering faculty by reflecting on classroom experiences in this study. We have dived deeper in this challenge every year and students are engaged but the wiki writing assignments implemented in the class were a challenge. The use of the wiki on Blackboard® Learn to manage the content for the blog article was useful on the individual level but presented some challenges to author as a team. The content in some of the student wikis seemed more individual than team, mainly due to the inattention to merging of the information to achieve coherency. Also, it was difficult to track individual contributions as students worked outside of the wiki on online collaborative platforms like Google drive, simply copying and pasting writing parts into the wiki. There was improved knowledge sharing as a result of wiki use that ended in bits of reflection on design decisions in some teams. The required citations and annotated bibliography in the wiki reduced the occurrence of plagiarism. It was clear the assignment quality rose from the first wiki to the third wiki as students gained familiarity with the tool. Moreover, its usefulness was apparent when students consolidated the information into the blog article. The final assignment, blog article, instead of written report was adopted as a tool to teach students public communication of engineering decisions. Next year, some class time will be dedicated to teaching students the editing features of a wiki. The rubric will be revised as criteria like persuasion and multimodal story-telling can be combined to give a single criterion. Other criteria to be combined include evidence and originality.

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