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Article

Sociotechnical Undergraduate Education for the Future of Natural Resource Production

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Abstract: The greatest challenges for contemporary and future natural resource production are sociotechnical by nature, from public perceptions of mining to responsible mineral supply chains. The term sociotechnical signals that engineered systems have inherent social dimensions that require careful analysis. Sociotechnical thinking is a prerequisite for understanding and promoting social justice and sustainability through one's professional practices. This article investigates whether and how two different projects enhanced sociotechnical learning in mining and petroleum engineering students. Assessment surveys suggest that most students ended the projects with greater appreciation for sociotechnical perspectives on the interconnection of engineering and corporate social responsibility (CSR). This suggests that undergraduate engineering education can be a generative place to prepare future professionals to see how engineering can promote social and environmental wellbeing. Comparing the different groups of students points to the power of authentic learning experiences with industry engineers and interdisciplinary teaching by faculty.

Keywords: engineering education; sociotechnical thinking; global sociotechnical competency; corporate social responsibility; sustainability in mining engineering education

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1. Introduction

The future of mining and other natural resource industries will require engineers who can take a sociotechnical approach to the challenges they face and the decisions they make in their working lives. The term sociotechnical recognizes that issues that appear to be technical in nature have an inherent social dimension [1–3]. For example, the coming energy transition will require massive amounts of minerals and metals, from the copper and iron necessary for power generation, transportation, and use, to the lithium, cobalt, and nickel required for electric vehicles. A recent review of around 30 energy transition minerals found that more than half are located close to vulnerable communities, specifically "on or near the lands of Indigenous and peasant peoples, two groups whose rights to consultation and free prior informed consent are embedded in United Nations declarations" [4]. Many of these populations already experience significant social and environmental injustices, and efforts to fast track mining projects central to the energy transition run the risk of adding more burdens [5]. Designing or selecting a particular technology that relies on one of these minerals, therefore, also implicates an entire supply chain of people, places, and injustices. To support more sustainable and responsible natural resource production, engineers need to be able to evaluate technologies and materials from a more holistic viewpoint, beyond narrow technical and economic considerations.

In general, there is a lack of preparation among engineering students to face the increasingly complex sociotechnical challenges of contemporary natural resource production. An ethnographic study of engineers practicing in the mining and oil and gas industries found that all had encountered sociotechnical challenges in their work, but felt underprepared to manage them [6,7]. The engineers described learning how to manage conflict, for example, as a trial by fire in which they learned on the fly, experimenting as they went along. This under-preparation largely stems from the structure of undergraduate engineering curricula in the United States–and likely elsewhere–placing a heavy emphasis on technical training, with very few opportunities for students to learn about the inherent social dimensions of the industries and infrastructures that will form the contours of their work [8]. Majors and courses frequently create an artificial technical/social dualism [9] that defines social and political concerns as external to engineers' domain [10].

Our educational research aims to address these structural challenges by nurturing sociotechnical thinking among engineering undergraduate students. We build on field evidence from the projects we have carried out in our countries, particularly in the United States and Colombia, in the teaching of mining and petroleum engineering, and put these into conversation with a broader movement of engineering educators seeking to disrupt the social/technical dualism by positioning engineering as "both technical and non-technical (taken to refer to the social, economic, political, ethical, etc.) from the start" [11]. Sociotechnical thinking involves students recognizing the "interplay between relevant social and technical factors in the problem to be solved" [8] and "to identify and address issues with an understanding of the complex ways in which the social and technical aspects of these issues are interconnected" by "holding both the technical and the social in one's mind simultaneously" [12]. Sociotechnical thinking is a prerequisite for students to be able to understand and promote social justice and sustainability through their professional practices.

Our research shows the value of using a sociotechnical perspective to teach and learn about themes related to sustainability and social responsibility. Engineering education research around the world assesses students' learning about these themes, though this field is too vast and growing too quickly to summarize here. The contributors to a special issue of the journal Sustainability focused on "Innovation in Engineering Education for Sustainable Development" (Sánchez-Carracedo 2020) captures current research in this area. A study of the International Center for Engineering Education in China found promise in its governance techniques to promote engineering education for sustainable development (Chen et al. 2022). A study of water and environmental engineers in Finland found correspondence between their sustainability education and required work skills, underlining the potential for engineers to play central roles in promoting sustainability (Vehmaa 2018). A group of US graduate students who traveled to India to study electronics manufacturing ended the trip reflecting on the ethical dimensions of regulations, gender roles, resources, and waste, including tensions among their multiple responsibilities (Berdanier 2018). Rich in-class discussions can also enhance student engagement and receptivity to sociotechnical thinking, especially given that the open-ended nature of these themes can prompt resistance (Blacklock et al. 2021).

In this article, we share the results of two efforts to nurture sociotechnical thinking among engineering undergraduate students. The first focuses on petroleum engineers at the Colorado School of Mines (Mines), where we integrated a critical approach to corporate social responsibility into multiple places in the curriculum. The second focuses on the Responsible Mining and Resilient Communities project that brought together engineering students from Mines, the United States Air Force Academy (USAFA), the University of Texas at Arlington (UTA), and the Universidad Nacional de Colombia-Medellín (UNAL). These students came from multiple disciplines but were all focused on artisanal and small-scale gold mining. We describe our methods and results case by case.

2. Materials and Methods

2.1. Sociotechnical Approaches to Corporate Social Responsibility in Petroleum Engineering

Our efforts to cultivate sociotechnical thinking in the undergraduate petroleum engineering program at Mines were part of a multi-year "Ethics of Extraction" research project, funded by the US National Science Foundation, that investigated the intersection of engineering and corporate social responsibility (CSR) [6]. Teaching students to recognize the inherent CSR dimensions of their work as engineers required taking a sociotechnical approach to both engineering, which is often viewed as a "technical" endeavor, and CSR, which can be viewed as a "social" endeavor. The type of CSR we taught was what Auld et al. [13] refer to as "new CSR," which encompasses activities that change core business practices to create social, economic, and environmental value for stakeholders as well as companies, in contrast with "old" CSR that is grounded in philanthropy. Changing core business practices in the mining and natural resource industries necessarily involves shifting engineering mindsets and practices.

For the project, we created an original survey instrument and custom enhancements for courses in petroleum and mining engineering at the Colorado School of Mines, Virginia Tech, South Dakota School of Mines and Technology, and Marietta College [6,14]. As a whole, our teaching reached over 1200 students. In our prior research [6], we found that students in all of the courses improved in defining CSR, especially in recognizing its intertwined social, environmental, and economic dimensions and in recognizing a broader array of stakeholders. Depending on the course, the majority (between 70–100%) ended the courses believing that CSR would be relevant to their careers as engineers, which potentially upsets the social/technical dualism that would define engineering as purely technical work and CSR as the responsibility of social scientists. We did not, however, find that students ended our courses expressing greater desires to work for companies with positive reputations for CSR, perhaps because they took a pragmatic view of their job market possibilities.

This article builds on that prior research by investigating whether and how our teaching shifted petroleum engineering students' understanding of the sociotechnical nature of both CSR and engineering. To assess the impact of our teaching enhancements on students' knowledge, attitudes, and skills, we developed and validated a survey instrument [14]. It included themes of corporate social responsibility, the ethical dimensions of engineering practice, engineers' agency in the workplace, students' career desires, and demographic information. In each course, all students took the survey at the beginning and end of the semester so that we could compare their responses before and after our course activities. We assigned each student who provided informed consent to participate in the research a unique and anonymous ID to match their pre- and post-course surveys (and track them year-by-year, for cohorts that participated in multiple classes) and calculated average responses for each class. We coded the qualitative responses. Finally, we collected end-of-semester reflections for the two senior level courses to generally assess student attitudes.

We focus on five classes of petroleum engineering students in two course offerings in this paper: three semesters of Summer Field Session I (summers 2017, 2018, and 2019), and two semesters of Senior Seminar (Fall 2016 and 2017). Both courses are required, meaning that they enroll the full cohort of petroleum engineering majors. The full demographic information for those courses can be found in [14], though we note that female students usually comprise a minority of the classes (30% and below) and there is a significant number of international students, especially from the Middle East (around 20%). The Summer Field Session enrolled students between their sophomore and junior year. The students traveled as a group and were introduced to the petroleum engineering industry through site visits, company tours, guest speakers, and facility tours. The Senior Seminar was designed to build their professional skills in the final year of their undergraduate program. The curriculum included approaching CSR through role-playing activities, a series of case studies based on actual experiences of an alumnus, industry speakers, and projects focused on controversial issues in the petroleum industry. For both of these course offerings, the intent was to promote interest, value, and motivation for learning about CSR; connect it to future careers; and integrate social and technical dimensions of petroleum engineering.

2.2. Sociotechnical Approaches to ASGM in Mining Engineering

The second area of research and teaching we analyze is the NSF-funded Responsible Mining, Resilient Communities (RMRC) project, which is an international and interdisciplinary effort to co-design socially responsible and sustainable gold mining practices with communities, engineers, and social scientists. The project focuses on artisanal- and small-scale gold mining (ASGM) in Colombia and Peru. While ASGM is an internally variegated field of practice, it generally refers to "labour-intensive, low-tech mineral exploration and processing" [15]. Most ASGM is done by individuals or small crews and happens without a title, making it an informal economic activity–and sometimes an illegal one–that exists in tension with government entities.

A key focus of the project is training undergraduate engineering students to approach ASGM from a sociotechnical perspective. In our research, we are investigating whether program activities enhance students' global sociotechnical competency. Building from prior research [16–18], we define global sociotechnical competency as being built from sociotechnical coordination; understanding and negotiating engineering and relevant national or local cultures; navigating ethics, standards, and regulations; and socially responsible engineering [19]. Table 1 provides an overview of the knowledge, skills, and attitudes that relate to each of these dimensions, using ASGM as an example.

Our prior research investigated whether participation in an intensive summer RMRC fieldwork session with Colombian faculty, students, and stakeholders enhanced U.S. undergraduate students' global sociotechnical competency. Because of the COVID-19 pandemic, we were able to test three different types of field sessions: one fully in person, in which US students traveled to Colombia (2019); one fully remote, in which students participated in activities on virtual platforms from their own work spaces (2020); and one hybrid, in which U.S. students studied together on a college campus but connected virtually with Colombian stakeholders (2021). We found that all three field sessions enhanced students' global sociotechnical competency. In particular, students ended the field sessions with a greater ability to identify the inherent social dimensions of problems that appear to be "technical" and with a greater ability to identify diverse stakeholders [19].

The current article builds on that prior research by investigating whether and how a week-long exchange at the Colorado School of Mines influenced how the Colombian students thought about the sociotechnical nature of ASGM. The delegation of visitors included twelve students and one faculty from the Universidad Nacional de Colombia's School of Mines in Medellín, plus one faculty from SENA's Centro Minero Ambiental in El Bagre (Colombia). They were hosted by RMRC faculty and students from Mines and the University of Texas at Arlington.

The delegation of Colombian students consisted of twelve students, ten women and two men, from the School of Mines of the Universidad Nacional de Colombia in Medellín. Eleven were from the Mining Engineering and Metallurgy program and one student came from the Environmental Engineering program. All the students had completed and passed more than 80% of the academic program and all of them were active members of the student chapter of SME (Society for Mining, Metallurgy, and Exploration). Most of them had participated in the joint work programs with the Colorado School of Mines in the two previous years. In their training they had a sociotechnical approach to mining projects in Colombia, primarily artisanal and small-scale gold mining. The students came from similar socioeconomic backgrounds. Some had relatives linked to the mining activity in Colombia, either as engineers or workers in a national mining company. One student came from an artisanal mining family. It is important to highlight that although all the students had a very good level of English, the exchange was the first opportunity for many of them to travel outside of the country.

Table 1. Global socio technical competency framework, originally published in [19].

Content Dimensions Learning Outcomes	Sociotechnical Coordination	Understanding and Negotiating Engineering and National Cultures	Navigating Ethics, Standards and Regulations	Socially Responsible Engineering
Knowledge	Understanding ASGM as a sociotechnical system	Understanding the history and political economy of ASGM in different countries Understanding the history and political economy of engineering in different countries with ASGM	Understanding legal dimensions of mining, labor & environmental management that affect ASGM	Understanding power differentials, how to have empathy, build trust, and treat expert and non-expert stakeholders involved in ASGM
Skills	Ability to identify different stakeholders in the ASGM life cycle and mediate among their needs and desires Ability to see how "technical" and "social" dimensions of ASGM co-constitute each other	Ability to operate differently in ASGM in different countries Ability to work with engineering faculty from different countries with ASGM	Ability to consult experts to ensure that sociotechnical innovations/design projects comply with legal and other regulatory standards relevant to ASGM	Ability to listen, engage in perspective taking, operate within different power positions, and work with expert and non-expert stakeholders involved in ASGM
Attitudes	Willingness to work with expert and non-expert stakeholders along the ASGM lifecycle Willingness to open up engineering decision making to a variety of social perspectives	Willingness to work with different ASGM perspectives in different countries and engineering faculty from different countries	Willingness to ensure that sociotechnical innovations/design projects comply with legal and other regulatory standards relevant to ASGM	Willingness and desire to engage in perspective taking Willingness and desire to work with expert and non-expert perspectives during project and after graduation Willingness and desire to use engineering to serve underprivileged populations Confidence in being able to make positive changes in communities through engineering

The exchange included a mix of field trips, lectures, and workshops. Participants took a field trip to a historic mining region in the Colorado mountains, where they were able to visit one of the world's largest molybdenum mines and the National Mining Museum and Hall of Fame. Students toured labs and centers at Mines, including a geoscience-themed makerspace, the Space Resources lab, the Earth Mechanics Institute, and the Geology Museum. They met and listened to presentations from engineering and social science faculty from the university's Humanitarian Engineering program, Payne Institute for Public Policy, and Instituto para Iniciativas Latino Americanas (Institute for Latin American Initiatives). They participated in workshops on asset-based community development, social innovation, and creative capacity building that were led by faculty and practitioners from MIT's D-Lab (whose mission is design for a more equitable world); Corps Africa (a non-profit that trains Africans in international development); and the Universidad Minuto de Dios (Colombia) Parque Científico de Innovación Social (Scientific Park for Social Innovation).

At the end of the exchange, students filled out a survey that included previously validated questions about their global socio technical competency.

3. Results

3.1. Sociotechnical Learning in Petroleum Engineering

We begin with a quantitative analysis of student responses to a survey question that asked students to evaluate CSR activities:

Q: CSR is a diverse field of practice that varies by industry, location, and company. In this survey we use an umbrella definition for CSR: an approach to business in which companies collaborate with stakeholders to create shared economic, social and environmental value. How would you evaluate the following activities as potential examples of CSR?

The possible responses ranged from primarily "social" activities (such as community training) to those that were sociotechnical and directly engaged engineering itself (such as rerouting a problematic pipeline). Students characterized each as being an excellent example of CSR, an okay example of CSR, or not CSR, with the option of selecting "I don't know". Of the possible responses, the three that most reflect a sociotechnical approach to engineering and CSR are underlined:

- A company providing training for members of a local community who want to open their own small businesses
- A team of engineers redesigning an industrial process to minimize potential spills of hazardous materials after learning that residents are worried about pollution
- A company giving college scholarships to children in the community where they operate
- A company accurately and transparently reporting how much money it spends in another country
- Employees doing charity or volunteer work in their free time
- A company constructing a municipal wastewater treatment plant for a city that desires but does not have one, so that the company can reuse the treated wastewater in its own production process
- An engineer reporting an unsafe practice to management or government authorities
- A company prioritizing local residents when making hires for new jobs
- An engineer changing the route of a pipeline to mitigate community conflict even though it will cost the company more money

Overall, the five courses were effective in helping students identify the three underlined "technical" decisions as also CSR decisions. In each course, more students ended the semester being able to identify at least two of the three sociotechnical CSR examples (the first two columns of Figure 1). In only one course (Fall 2017 Senior Seminar) did large numbers of students move away from "OK example" to either "excellent," "not CSR," or "I don't know." We explain potential reasons for this outcome below.

The full data set is available in Table 2 summarizes student assessments from five Petroleum Engineering classes for the three underlined options. We received unique responses from 427 students over the five classes.

Table 2 shows that the changes we observed in the student responses from the beginning to the end of the semester varied by both course and year. For example, fewer students in the Fall 2016 Senior Seminar ended the semester assessing redesigning an industrial process as excellent CSR (down to 70% from 81%), but more judged building a water treatment plant and rerouting a pipeline as excellent (up to 64% and 64% from 58% and 53%, respectively). The 2017 cohort showed improvements in judgements of excellent for each example. In the 2017 and 2019 summer field sessions, there were larger jumps in improvement for recognizing each example as excellent, but in 2018 fewer students judged building the treatment plant as excellent at the end.

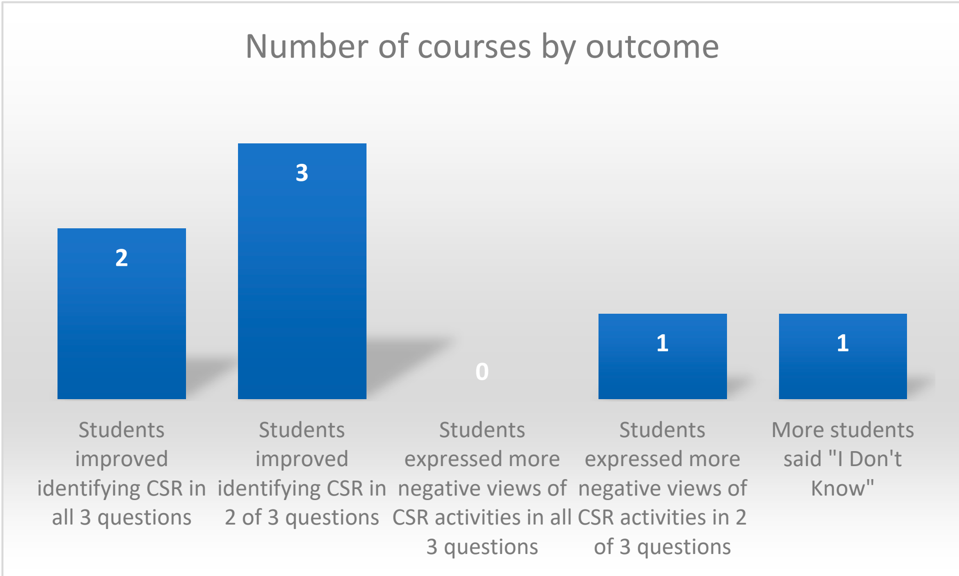

Figure 1. Course outcomes for Mines students (out of a total of 5 courses).

There was much more uncertainty indicated for the 2017 Senior Seminar cohort across all three questions, as indicated in the increase from pre- to post-survey responses of "not CSR" and "I don't know." Growing awareness of the complexities of practicing engineering, along with the beginning of a serious downturn in the petroleum industry may have led to more polarization in the students' views of CSR. During this time, several students' job offers were rescinded and oil and gas companies had more and more challenges keeping their doors open, and less money to incorporate multiple stakeholders' needs. This polarization is illustrated well with this student end-of-semester reflection on the seminar course:

Personally, I think this class is very interesting and perhaps my favorite, contrary to most of the people I've asked. I feel it is super important to broaden our horizon into the non-technical aspects of the industry, especially for those who would like to be leaders in the industry and make a positive impact. However, some/most of my colleagues think otherwise . . . . I believe that a lot of the student's frustrations with the course are tied to lack of opportunities in the industry, and the fact that this course "steals" time for other studying to be conducted. Especially in a time where students are trying to boost their GPA, with the belief that it is their best method to increase chances of employment.

There was more uncertainty and skepticism present in each of the senior seminars, which is likely due to the timing of the courses in the students' undergraduate progression. The field session is taken by students just entering the petroleum engineering major, while the seminar is taken by students who are typically in their last year of the program. This difference may have led to more skeptical evaluations of potential CSR activities by the senior students, as many of them would have had much more exposure to technical topics along with possible internships related to the petroleum industry. Thus their views are much more sophisticated, technical, and prone to influence from companies and current events. With increased technical knowledge, yet limited broad industrial knowledge, for example, seniors may only interpret "redesigning industrial processes" as a technical intervention, rather than making the connections to the ways these changes may serve the public. Additionally, the seminar course was offered during the most intensive semester of petroleum engineering courses for these students. This led to many not taking it very seriously. One student commented that offering it a semester later could lead to more students valuing the course material and taking it personally: " I believe a relatively reduced course load in the Spring, combined with the fact that (some) students will finally realize that "the end of academics is near", will provide a sobering feeling that they need to broaden horizon to learn more about 'what's out there".

Table 2. Student assessments of CSR activities.

		Redesigning Industrial Processes		Building Treatment Plant		Rerouting Pipeline	
		Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
Senior Seminar Fall 2016	Excellent Example	81.08%	69.90%	58.11%	63.59%	52.74%	63.78%
	OK Example	13.51%	19.90%	25.68%	25.13%	30.14%	27.55%
	Not CSR	4.73%	8.67%	13.51%	9.23%	13.01%	4.59%
	I don't know	0.68%	1.53%	2.70%	2.05%	4.11%	4.08%
	Total students	148	196	148	195	146	196
Senior Seminar Fall 2017	Excellent Example	82.05%	79.49%	61.54%	74.36%	76.92%	80.77%
	OK Example	16.67%	7.69%	33.33%	12.82%	17.95%	12.82%
	Not CSR	1.28%	8.97%	5.13%	7.69%	3.85%	3.85%
	I don't know	0.00%	3.85%	0.00%	5.13%	1.28%	2.56%
	Total students	78	78	78	78	78	78
Summer Field Session 2017	Excellent Example	61.54%	74.36%	61.54%	76.92%	51.28%	71.79%
	OK Example	23.08%	20.51%	28.21%	20.51%	30.77%	23.08%
	Not CSR	15.38%	5.13%	7.69%	2.56%	12.82%	2.56%
	I don't know	0.00%	0.00%	2.56%	0.00%	5.13%	2.56%
	Total students	39	39	39	39	39	39
Summer Field Session 2018	Excellent Example	73.77%	83.61%	50.82%	45.90%	55.74%	73.33%
	OK Example	19.67%	13.11%	27.87%	36.07%	29.51%	18.33%
	Not CSR	6.56%	3.28%	16.39%	14.75%	9.84%	5.00%
	I don't know	0.00%	0.00%	4.92%	3.28%	4.92%	3.33%
	Total students	61	61	61	61	61	60
Summer Field Session 2019	Excellent Example	77.78%	88.89%	53.70%	64.81%	62.96%	70.37%
	OK Example	14.81%	7.41%	29.63%	27.78%	27.78%	25.93%
	Not CSR	5.56%	1.85%	14.81%	7.41%	7.41%	1.85%
	I don't know	1.85%	1.85%	1.85%	0.00%	1.85%	1.85%
	Total students	54	54	54	54	54	54

There were also several end-of-semester reflections from students about the difficulty of balancing the needs and desires of so many groups with different aims, which also point to an increasing sophistication in perception of how CSR plays a role in the work they hoped to do. This is summed up well with this student perspective: "The one thing I struggle with is finding a balance between the business side of myself, and the empathetic side of myself. The business side can easily come up with the key stakeholders that need to be addressed, but often overlooks the fact that the people with no voice and no one to protect them, desperately need advocates within the oil and gas industry to make sure they are not overrun. On the other hand, the empathetic side of me could happily take forever, and come up with a solution which perfectly fits everyone's needs-even though a perfect solution that makes everyone happy usually doesn't exist".

Student reflections and general instructor observations also provide some insight into how students' thinking shifted regarding CSR, socio-technical thinking, and reconciling

CSR and its complexities into their professional practice. Many students originally perceived CSR to be about environmental stewardship but came to appreciate that CSR also included social dimensions. Initially, students justified CSR as a way to make profits, share wealth, satisfy shareholders, and create jobs. That view became more nuanced as they also learned the importance of protecting reputation, mitigating risk, and maintaining a social license to operate. They shifted from viewing CSR as a way to promote the public good in general, to CSR as a specific way to implement sustainable community development and improve local quality of life. Concurrently, there was a noted shift from defining CSR as sharing benefits and being philanthropic to CSR better aligning with the Auld et al. definition of "new" CSR or redesigning core business practices. Student reflections indicated that many believed CSR to encompass more complex social responsibilities such as maintaining transparency and seeking mutual understanding. All of this was undergirded by a shift from examining problems as technical challenges to sociotechnical problems. Students observed that issues many stakeholders face regarding petroleum engineering projects are more-than-technical, and thus, they needed to find more-than-technical ways to address concerns. They also noted that many people had major concerns regarding the petroleum industry and that people want to be heard and understood, rather than being "assaulted" by facts. This suggests that they were able to see the "problem" of petroleum engineering depended on who was defining it, and that stakeholders could define the problem differently than a petroleum engineer.

3.2. Sociotechnical Learning in Mining Engineering

All students who participated in the exchange completed the survey and wrote brief reflections at the end of the session. Table 3 summarizes the average student responses to the survey questions related to global sociotechnical competency, which focused on working in unfamiliar places, collaborating with people from different backgrounds, empathizing, and feeling confident in being an engineer.

We found that students ended the exchange expressing strong desires to work and live abroad (5.0 out of 5.0) and serve underprivileged populations (4.9). Importantly, they also expressed confidence in working with engineering students from different backgrounds (4.8) and learning from professors with different backgrounds (4.9). Empathy is a crucial dimension of global sociotechnical competency, and students expressed comfort and enjoyment learning about unfamiliar people and places (4.6), talking with people from different backgrounds (4.7), asking people questions about their experiences (4.4), and seeing other people's point of view (4.6). They also expressed strong self-efficacy, including confidence in their abilities as engineers (4.4), and positive views of engineering as a fulfilling profession (4.5) that makes it possible to make positive changes in com-munities (5.0).

The survey also explicitly asked students about whether the visit provided them "new perspectives on engineering as a sociotechnical activity" and helped them "understand the social, environmental, and economic dimensions of mining." Students responded positively to both questions, with average responses of 4.9 out of 5 for the former and 4.8 out of 5 for the latter.

It seems likely that this more holistic view of engineering in general and ASGM in particular is related to the overwhelming sense that the exchange provided professional growth opportunities. In their written comments, students described the exchange as being a "mind changer" that gave them the "opportunity to see new perspectives in the mining industry," and as an experience that opened their eyes to "new possibilities" for their professional careers. Many of them referenced the sociotechnical theme of week–and seeing how they can contribute to ethical goals through their professional practice–as being transformative. The following are quotes from students:

- "Now, I understand that there must be a balance between many aspects such as: ethical, humanitarian and environmental."
- "It is a mind change to become a person that contributes to community development from science."

- "I had a huge desire to contribute to science but [now I know] that I want to con-tribute to science but also serve underprivileged communities."
- "The most valuable aspect to me was being able to integrate all the social, environmental and technical aspects of mining engineering. It was a very enriching experience that would allow me to continue improving as a professional and a person."
- "This visit reinforced my ideals of combining social knowledge with technical knowledge and I was able to make many contacts with excellent professors from different universities."
- "This visit allowed me to open my mind to more possibilities in the mining sector that I didn't know so far. I was able to discover how topics I have always been passionate about can have applications in mining."

Table 3. Average student self-assessments on a scale of 1 to 5 (1 = not at all like me; 3 = neutral; 5 = very much like me).

Question (1 Is Low, 5 Is High)	Average
I like to learn about people and places unfamiliar to me.	4.6
I feel comfortable talking with people from different backgrounds.	4.7
I like to ask people questions about their experiences.	4.4
It is easy for me to see other people's points of view.	4.6
I feel confident working with engineering students from different backgrounds.	4.8
I enjoy learning from professors from different backgrounds.	4.9
I would like to study or work internationally at some point in my career.	5.0
I would like a career that allows me to serve underprivileged populations.	4.9
I am confident in my abilities as an engineer.	4.4
I find fulfillment in engineering.	4.5
I can make positive changes in communities through engineering.	5.0

After this experience, the students reflected on how they had broadened their knowledge of new ways of learning. They developed a greater tolerance to work in difficult conditions and an approach to other methodologies of interaction with the environment, both large-scale, which some of them already knew, and small-scale, which represented a novelty for others. All of them highlight this experience as very positive and formative and appreciate the sustainability of mining as a central axis of their professional performance.

4. Discussion

Both sets of students–the Mines petroleum engineering students and the Colombian mining engineering students–ended their experiences with a greater knowledge of the sociotechnical nature of their chosen professions. The significant differences between the students, their experiences, and the assessments guard against tight comparisons. For example, almost all of the Colombian students were much more energized by the experience of coming to view mining engineering as a sociotechnical activity and described it as a formative moment in their professional development. We noted similar excitement in a portion of the petroleum engineering students, but that was tempered by resistance to the course material and activities among others. In a sense, more petroleum engineering students articulated more strongly that the "social" material was external to their core identity and responsibilities as engineers. This difference could be attributed to the different paths that led to the students participating in the sociotechnical learning opportunities: the Colombian students had all volunteered for the exchange and were not being graded on their performance, whereas the Mines students were required to take the courses for grades. Grades took on an added significance when the petroleum market downturn made competition for jobs fierce.

While one of the interesting findings among the Mines students was the increased polarization of opinion and uncertainty by their senior year, our instruments for the Colombian exchange did not allow us to measure uncertainty and polarization. We do note relative uniformity in the students' answers to the survey question: almost all students responded to questions with either a 4 or 5 on a 5-point scale, with 5 representing the most positive answer. It could be that the students were eager to show their appreciation for the trip, and so answered the questions extra positively.

The comparison of the student groups seems to point to the significance of real-world experiences as transformative for students' learning. Both the petroleum engineering field session and the Colombian mining exchange included visits to industrial sites and interactions with industry professionals, in addition to learning from their professors. In the senior seminars, the professor created multiple opportunities for industry connections–such as through invited guest speakers–but most of the activities took place in the classroom. These observations underscore our previous research that also showed that connections with practicing engineers was especially transformative for student learning about social responsibility [6].

Finally, we underline that all of the petroleum engineering courses and the Colombian exchange were the result of interdisciplinary collaborations among faculty from engineering and social science backgrounds. These kinds of collaborations are particularly well-suited to sociotechnical teaching and learning [3,8].

5. Conclusions

Some of the greatest contemporary challenges facing the mining and petroleum industries are sociotechnical in nature, dealing with thorny issues of public acceptance and social and environmental justice. Training the next generation of engineering students to approach problems from a sociotechnical perspective is a key strategy for addressing those challenges and developing industry projects that are responsive to local concerns and needs. Undergraduate education is a time in which students are not just developing technical expertise, but their own identities as engineers. Presenting students with social content directly inside of their majors is a powerful strategy for defining societal concerns as central to their responsibilities as engineers. Our teaching and research with two different groups of students–petroleum engineering students enrolled at the Colorado School of Mines (though hailing from around the U.S. and the world) and Colombian mining, metallurgical, and environmental engineering students from their School of Mines–found that collaborative, interdisciplinary teaching about authentic problems enhanced students' abilities to understand their professions from a sociotechnical perspective. This recognition is a crucial step to being able to then practice engineering in a way that promotes sustainability and social justice.

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