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An Industry Perspective on the Current US Metal Mining Engineering Education

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Abstract
Mining industry requires constant adaptation to its practices in response to the dynamic change of the societal demand. Little information exists regarding how the US metal mining engineering education is prepared to meet with its industry needs due to the increase in critical minerals driven by the green energy transitions. This study aims to provide industrial perspectives on the current US metal mining engineering education and areas for improvement. An online survey with both closed- and open-ended questions were designed to seek opinions from the US mining industry. Findings indicated a shortage of qualified graduates from the current US metal mining engineering education system. The qualifications need to be improved include engineering sciences underlying mining methods, mining design experience, mining feasibility study, the connection between theory and practice, and understanding of the overall mining operation. The survey also identified future desired qualifications. The most desired ones in the next 5 years include an ability to acquire and apply new knowledge as needed and sufficient experience in the field. Respondents, regardless of the nature of their affiliated mining companies, unanimously recommended that collaborations between the industry and academia should be enhanced. The analysis of the results concluded four recommendations: (1) involve more multiple stakeholders in reforming mining education programs, (2) reinforce field experiences as a key part of mining engineering education programs, (3) enhance a closer collaboration between academia and industry, and (4) integrate emerging technologies (e.g., artificial intelligence/virtual reality) guided by pedagogical theories into new mining engineering curriculums.

Keywords Metal mining engineering education · Qualification · Needs assessment · Industry academia collaboration

1 Introduction and Background

Mining industry has been playing an essential role in maintaining the wellbeing of billions of people on earth. The industry produces in essence all non-plant-based resources. According to the statistics from the U.S. Minerals Education Coalition (2020), the industry produces approximately 3.19 million pounds of minerals, metals, and fuels on average that an American will need during their lifetime [1]. The latest societal transition to green energy further increases the demand of critical minerals that are required by the green technologies. For example, the production of lithium and cobalt (i.e., key elements for lithium-ion battery technology) over the coming two decades have to increase by more than 2000% and 300 to 800%, respectively; the rare earth element (i.e., key components for wind turbines)-neodymium by 1000 to 4000%, and the indium by as much as 8000% [2–4]. This drastic increase is unprecedented in a sense that the challenges cannot be tackled by the mining industry alone. Instead, a collaborative effort among multiple stakeholders, including mining companies, government agencies, and higher education institutions, is required [4].

One of the significant challenges faced by the mining industry across many nations is the shortage of qualified workforce [5–9], which concerns issues related to not only the quantity but also the quality. In the United States, the quantity seems to be more serious because there are only 14 US universities left, according to the National Mining Association (2022), that still offer mining and related (such as metallurgical) engineering program after the U.S. Bureau of

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Mines was closed in the 1990s. These schools combined only produce approximately 200–300 graduates per year, which is unlikely to meet the surging demand of the mining workforce of approximately 221,000 (including other relevant profession such as trucker drivers, service providers, trades personnel, etc.) in 2029 as projected by the Energy Information Administration (EIA) [10]. In addition to the quantity, the quality may present as a challenge, especially considering topics related to minerals (e.g., lithium, rare earth minerals) and computers (e.g., machining learning, artificial intelligence) are not part of the typical mining engineering curriculum. This shortage of qualified workface hinders the US domestic production of critical minerals which consequently impounds the societal transition to green energy. Therefore, new efforts are required to improve the mining engineering education so that a pipeline of qualified workforce can be trained. Understanding the industry requirements is the first step towards this new endeavor which is the focus of this study; it is also necessary to examine the current state of the mining engineering education around the world so that baseline information can be obtained for recommendations.

The paper is organized as the following. In Section 2, we summarize the proposed strategies in the literature to improve the mining engineering education. We then present the purpose statement and research questions of this study in Section 3. In Section 4, we provide details about data collection, participants, survey development, and our strategies for data analyses. The survey findings are presented and summarized in Section 5. We conclude in Section 6 with our recommendations.

2 Proposed Strategies to Improve Mining Engineering Education

Mining engineering education faces challenges in various aspects, which has been observed in many countries. To tackle these challenges, significant efforts have been made [5, 11–14]. In Table 1, we review and summarize some recent educational reforms and proposed strategies by different countries, institutions, criteria/standards for their curricula, and key elements.

In Canada, the University of British Columbia took several actions to improve their mining engineering education [11]. These included soliciting feedback from faculty, students, and the industry advisory committee on how their mining engineering undergraduate curriculum can be improved, evaluating the program outcomes with the accreditation criteria for Canadian Engineering Accreditation Board to identify potential areas for improvement, and employing a learning community approach to restructure the curriculum [11]. These actions led to several major changes, such as combining a mineralogy and a petrology course to one new course which focused on process mineralogy; splitting the introduction of mining, and mineral processing course into two courses; and adding emphasis in leadership and project management skills and incorporating more team and project-oriented assignments in the third- and fourth-year design courses.

In China, the mining engineering program at Jiangxi University of Science and Technology implemented a key change with an aim to improve the technical and managerial skills of their students. The change involved reducing the university education from 4 to 3 years but adding an additional 1-year talent training at the mining companies [17].

Another ambitious example is an international project—Master in Entrepreneurship, Innovation and Technology Integration in Mining [20]. The MEITIM project is led by the Technical University of Madrid in Spain, in partnership with Wroclaw University of Science and Technology in Poland, and Lappeenranta University in Finland [6]. In addition to the three universities, several companies (e.g., Mestso Minerals Oy, Atlantic Copper S.L.U.) and research institutions (e.g., Geological Survey of Finland, Spanish National Research Council) are partnership organizations of this project [20]. According to the team, "The main objective of the project is to create from scratch a completely new master's degree program, which will combine entrepreneurship, innovation and technology integration in the mining industry." [6]. This project is supported by European Institute of Innovation and Technology (EIT) Raw Materials whose strategic goal is to secure critical minerals needed for the sustainable and green energy technologies.

Other strategies include those that focus on adopting a theoretical framework for reforming curriculum [12], developing specific tools for enhancing student knowledge and skills [15], developing new courses [16], locating funding resource [18], or proposing a co-op model [19]. For example, to enhance real-world problem solving and transfer of knowledge for mining engineering students at the University of Pretoria in South Africa, the CDIO (conceiving, designing, implementing, and operating) framework [12] was employed to guide the development of curricula and teaching. Main characteristics of a CDIO-based education are as follows: (1) a curriculum organized around mutually supporting courses but with CDIO activities highly interwoven, (2) enriching student design-build-test projects, (3) integrating learning of professional skills such as teamwork and communication, (4) integrating active and experiential learning, and (5) constantly improving through quality assurance process with higher aims than accreditation (CDIO, n.d.). In the work of Akkoyun and Careddu (2015), a simulation-based computer program was designed and proposed as an educational tool for teaching and learning of mining engineering related subjects [15]. Binder et al. (2017) presented two courses designed to help master's students in mining engineering develop competence in the field of sustainability [16]. Kansake et al. (2019) proposed a mining education fund model for funding innovative research

Table 1 Summary table of proposed strategies to improve mining education in chronological order

Country	Institution	Criteria/standards	Key elements
Turkey [15]	Dicle University	No information	A simulation-based computer program was created for lectures in mining engineering, such as surface mining, drilling, and blasting, mining economy, introduction to mineral processing and mining machinery. Program output includes important values (e.g., total drillholes, excavated in tons, oversize in tons, cost for fuel) and a pie chart for the main cost values
Canada [11]	The Norman B. Keevil Institute of Mining Engineering at the University of British Columbia	Canadian Engineering Accreditation Board	Collaborative and integrative model of curricular learning communities
Germany [16]	Clausthal University of Technology	• Interdisciplinary content of learning • Involvement of Students in the context of learning • Active, experiential, inquiry-based process of education • Practice of sustainability • Partnerships with local, regional communities (Timpson et al., 2006)	Sustainability aspects were integrated into the Master Mining Engineering Curriculum with two courses: "Sustainability in Underground Mining" and "Advanced Underground Mining." Both courses were taught in 28 contact hours with 62 h of self-study time
South Africa [12]	University of Pretoria	Engineering council of South Africa: Standards and Procedure System	An integrated framework for problem-solving within discipline-specific learner education and development modules at the Department of Mining Engineering at University of Pretoria
China [17]	Jiangxi University of Science and Technology	National engineering education accreditation, outstanding engineers training program, training plan, and an exploration of training mechanism	"3 + 1" training mode for modular teaching: Learning the school public basic course and professional basic courses for 3 years and learning and practicing in the cooperative practice base or mining enterprise for 1 year
Australia [5]	School of Chemical Engineering at the University of Queensland	Common core knowledge and skills to define metallurgical process engineering programs: • specialist metallurgical process knowledge and skills • process control/ reaction engineering • process modeling and optimization • process design and synthesis	• Year 1: basic and engineering sciences • Year 2: process engineering and modeling fundamentals • Years 3 and 4: specialist metallurgical courses and courses from related disciplines as appropriate for local industry requirements Dual major program in chemical and metallurgical engineering
Ghana [18]	University of Mines and Technology, Kwame Nkrumah University of Science and Technology, Takoradi Technical University, and the University of Ghana	No information	Institutions in Ghana require facilities (e.g., experimental mines, simulation centers) that addresses the needs of the future mining environment. A Mining Education Fund model was proposed to fund innovative research and teaching in autonomous mining
Spain, Poland, Finland [6]	Technical University of Madrid (Spain), Wrocław University of Science and Technology (Poland), and Lappeenranta University (Finland)	European Green Deal International Council on Mining and Metals	A new master in Entrepreneurship, Innovation and Technology Integration in Mining, conducted under the leadership of the Technical University of Madrid (Spain)

Table 1 (continued)

Country	Institution	Criteria/standards	Key elements
NA [19]	No information	No information	A co-op model for undergraduate mining engineering education: mines employing people straight from school, and after a probation period of 6 months, providing paid or unpaid time to study 2–3 university courses every half year. These could be offered in two-week-block periods, either at the university, remotely (live), or on-line

and teaching in autonomous mining [18]. With the increasing number of online courses, the pandemic to accelerate the online delivery mode, and workforce shortage, Spearing et al. (2021) proposed a modern co-op model in which students spent less time in universities but more time working on site with compensation, and they can study either at the university or remotely every half year after leaving schools [19].

3 Purpose of the Present Study

It is evident that higher education institutions around the world have started mining education reform. In seeking potential actions for the US metal mining engineering education, it is critical to first comprehend the perspectives from the industry because mining engineering has a strong applied aspect tied to its industry. This paper intends to obtain such information through a survey to the US mining industry. It should be noted that the focus of this study is on the metal mining engineering education and that the education of other mining sectors is not studied here. Specifically, our study aims to address the following four research questions:

(1) What are the required qualifications a mining engineering graduate should have to be hired by the mining industry?
(2) What are the areas for improvement in the current mining engineering education at higher education institutions?
(3) What are the recommendations proposed by industry for improving mining engineering education?
(4) Do different sectors in mining industry have different perspectives on the required qualifications that a mining engineering graduate should have?

4 Method

4.1 Data Collection

This study was determined as not required for human research protection oversight by the institutional review board. The distribution of the survey was assisted by the members of the two advisory boards of authors' university. The members were advised to further distribute the survey within their professional networks. The members of the two advisory boards and participants not only serve for the authors' institution but other U.S. metal mining universities. The survey also asked the participants to provide their comments on the U.S. metal mining engineering graduates without being specific to those graduated from the authors' institution. Therefore, the survey findings can potentially represent the situation of the other U.S. metal mining schools. The survey took approximately 10 min to complete.

To estimate the minimum sample size required for our study, we conducted a priori power analysis in G*Power 3.1.9.7 [21, 22]. We used alpha = 0.05, statistical power = 0.8, and equal sample sizes for the two groups of respondents' affiliated companies. When the effect size of *d* is 0.5, 0.8, 1, and 1.2, the minimum sample size required per group for an independent samples *t*-test is 64, 26, 17, and 12, respectively [23].

4.2 Participants

A total of 31 individuals responded to the survey. Three participants responded to two or fewer questions, and 28 participants responded to all the Likert-type questions. Reponses provided by the 28 participants were used in the study. Sixteen of the 28 participants further provided their responses to the open-ended questions.

Among the 28 participants, there were 4 (14.3%) junior mining engineers, 1 (3.6%) intermediate mining engineer, 9 (32.1%) senior mining engineers, 4 (14.3%) engineering managers/supervisors, 6 (21.4%) executive/senior managers, 1 (3.6%) environment specialist, 2 (7.1%) geologists, and 1 (3.6%) consulting engineer. When the 28 participants were asked about the nature of their company, 15 (53.6%) reported mining/metallurgical operation, 5 (17.9%) mining/metallurgical equipment supplier, 5 (17.9%) mining/metallurgical consulting, 2 (7.1%) engineering procurement, construction, and management (EPCM), and 1 (3.6%) research and development (R & D). Figure 1 presents the pie chart of the distribution of participants' companies.

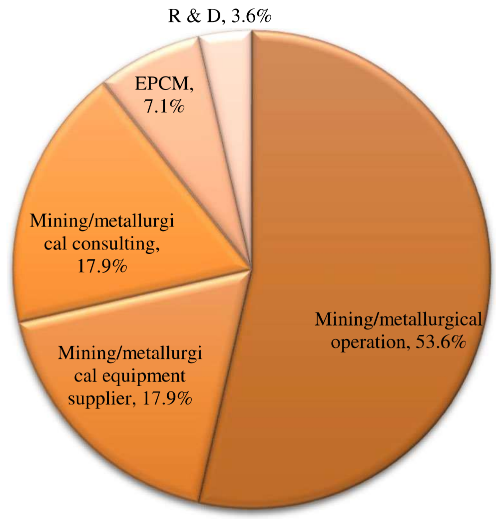

Fig. 1 Pie chart of respondents' companies

4.3 Survey Development

A panel consisted of four university educators in the areas of mining engineering (an assistant professor), education (an assistant professor and a full professor), and computer science (a full professor) was formed to design the survey questions. The intention to combine perspectives from different disciplines was to capture opportunities for improvements that otherwise would not be possible with a mining engineering educator alone. In developing the survey questions, the mining engineering professor first drafted a list of questions based on some typical metal mining engineering curriculums. Next, the rest of the panel reviewed the initial draft individually and then the panel met together to discuss each question. After the meeting, the mining engineering professor revised questions based on the panel discussion. A similar procedure was conducted two more times to form the final draft. The director of the mining school at the authors' university was invited to provide feedback to the final draft. Feedback and suggestions provided by the director were incorporated into the final survey.

The final survey consists of 22 Likert-type close-ended and five open-ended questions (shown in the Appendix). The Likert-type question target areas including knowledge, skills, and qualifications of the current graduates, the application of new technologies (e.g., artificial intelligence/virtual reality) in teaching and training, mining workforce shortage, and collaboration between academia and industry. Seven response options are provided for each Likert-type question, including 1 = strongly disagree, 2 = disagree, 3 = somewhat disagree, 4 = neither agree nor disagree, 5 = somewhat agree, 6 = agree, and 7 = strongly agree. The five open-ended questions asked participants to comment on the following: (1) areas which include any missing qualifications of the current graduates, (2) the required knowledge and skills in the next 5 years, (3) any challenges that currently cannot be tackled but will be by new technologies in the future, (4) the preferred software packages for training and operation, and (5) recommendations for universities to improve their mining education.

4.4 Strategies for Data Analysis

To analyze data from the Likert-type questions, the mean score of each question along with its 95% confidence interval (CI) were calculated. For a question related to knowledge, skills, and qualifications of mining engineering graduates, we deemed an attention is required when the lower limit of the 95% CI was below 4 (i.e., neither agree nor disagree). For the rest of questions (e.g., the application of artificial intelligence/virtual reality can be used to enhance mining teaching and learning experience), we considered the participants agree if the lower limit of the 95% CI was higher than 4.

Because participants' responses may relate to the nature of their companies, we divided the nature of participants' companies into two groups (i.e., affiliated with or not affiliated with a mining/metallurgical operation company) and examined if there were significant differences between the two groups on their responses to general qualifications of graduates. There were 15 participants who were affiliated with a mining/metallurgical operation company and 13 participants who were not affiliated with a mining/metallurgical operation company. Therefore, if the population effect size of *d* is at least 1.2, we met the minimum sample size requirement to achieve a statistical power of 0.8. The questions related to general qualifications of graduates were derived from the overall curriculums. The four questions that the survey asked in this area include the following: "Current graduates have demonstrated a reasonable grasp on the connection between theory and practice." "Current graduates have sufficient communication skills for their first professional careers." "Mining/metallurgical engineering students should have a good understanding of the overall mining operation, e.g., the mine-to-mill approach." "Current mining/metallurgical engineering graduates have demonstrated sufficient understanding of the overall mining operation."

For open-ended questions, we matched the survey responses with seven criteria in the Accreditation Board for Engineering andTechnology (ABET) [24]designed for evaluating the student leaning outcome. The number of times that survey responses can be matched with each of the seven student outcomes was counted. One respondent's response can only be counted once for one student outcome. Yet one respondent's response may be matched to multiple outcomes, depending on the fit of the response to the outcomes. A higher number implies that participants perceived a need to strengthen that specific outcome. For the responses that cannot be matched with any of the areas, we listed those separately. When participants from multiple types of mining companies all mentioned something related to a specific student outcome/area, it also indicates a need to strengthen that specific outcome/area, regardless of participants affiliated companies. Therefore, we color coded the responses by participants' companies.

5 Results

5.1 Results from Likert-Type Questions

5.1.1 Knowledge of Mining Engineering upon First Employment

Figure 2 shows the survey responses to the qualifications of mining engineering graduates upon their first professional employment. The results indicate that the participants generally agreed that the mining engineering graduates are equipped with qualifications in the areas of mining methods (4.86 ± 0.55, error bar stands for the 95% CI) and mine design in both underground and surface mines (4.79 ± 0.49). For engineering underlying sciences (4.50 ± 0.57), mining design experience (4.29 ± 0.54), and mining feasibility study (4.25 ± 0.56), the results reflect a somewhat neutral viewpoint and the lower limits of the three were below 4. We consider these three areas can be improved and marked them in orange in Fig. 2.

5.1.2 General Qualifications of Graduates Derived from the Overall Curriculum

Responses related to the qualifications of graduates derived from the overall curriculums are presented in Fig. 3. Participants did not agree that the current curriculum prepare students to bridge the gap between theory and real-world practice, i.e., 4.11 ± 0.61. It is marked in orange in Fig. 3. The responses indicate the expectation of the industry that students graduated with the current curriculum should attain a good understanding of the overall mining operation (6.11 ± 0.41). However, this expectation had not been met as the responses suggested (4.21 ± 0.55), marked in orange in Fig. 3. In terms of the

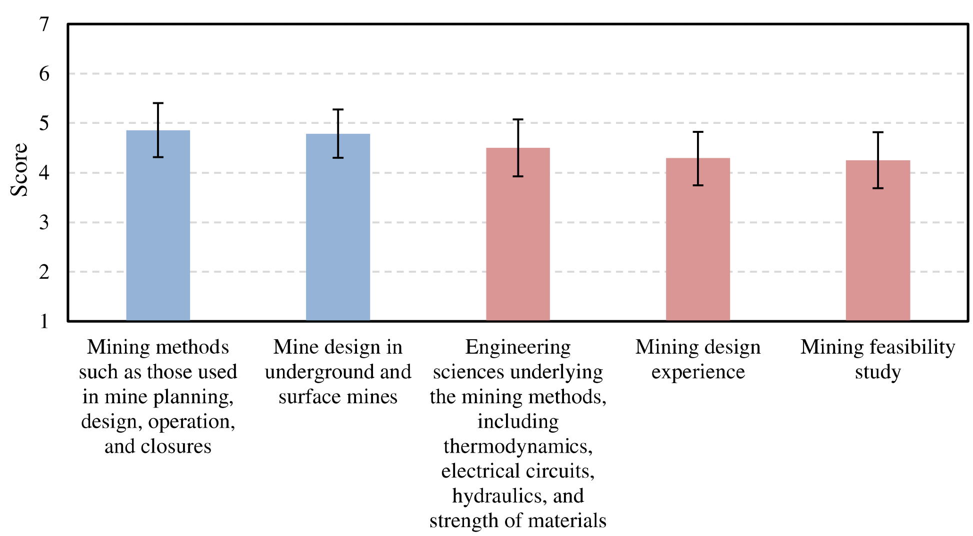

Fig. 2 Qualifications of mining engineering graduates upon their first professional employment. Scores of 1 = strongly disagree, 4 = neither agree nor disagree, 7 = strongly agree. Error bars show the 95% CIs. Orange bars have the lower limits lower than 4, which indicate areas require improvement

communication skills, the responses suggest that the industry in general was satisfied with the current curriculum (5.04 ± 0.60).

5.1.3 Graduate Awareness of Challenges Faced by Industry

The survey also asked the industry to comment whether the graduates aware of the challenges faced by the mining industry. Three major challenges, including decreased ore grade complicating the mining operation, growing challenges for tailing management, and increasing responsibilities for sustainability and environment are included in the survey. The survey results imply that the current curriculums made the graduate aware of challenges faced by the mining and metallurgical industry, i.e., 4.79 ± 0.58, 4.75 ± 0.64, and 4.96 ± 0.59, for the respective challenges.

5.1.4 Applying AI/VR, Shortage of Workforces, and Collaboration Between Academia and Industry

In exploring new potential methodology to improve mining engineering education, one question asks the industry whether they think the emerging technologies, such as artificial intelligence and virtual reality (AI/VR), can be effective tools. The responses signal an encouraging attitude, i.e., 5.14 ± 0.50. Additionally, the industry seems to be willing to adapt these technologies into their own training program, i.e., question 9 with a score of 4.75 ± 0.54.

Three questions concern the challenges related to the workforce for the mining sector. The industry agreed (5.82 ± 0.46) that there is a widespread workforce shortage for the industry. The response also indicated that the industry is very willing to collaborate with the higher institutions to better understand the challenges in the workforce (question 11, 6.36 ± 0.34) so to develop potential solutions (question 12, 6.29 ± 0.35). Responses of these questions are presented in Fig. 4. It should be noted that these two questions related to collaboration between universities and industry yielded the highest scores and narrowest CIs across the 17 Likert-type questions analyzed in the present study. This implies that the participants unanimously agreed the importance of collaboration between academia and industry.

5.1.5 Comparing Ratings of Qualifications of Graduates from the Overall Curriculums between Participants Who Affiliated with Mining/Metallurgical Operation Companies and Their Counterpart

We perform an independent samples *t*-test to examine the mean difference between participants who were and were not affiliated with a mining/metallurgical operation company on each of the four questions related to general qualifications of graduates derived from the overall curriculums. A significance level of 0.05 is used. Results reveals that respondents affiliated with the mining/metallurgical operation companies tended to give lower ratings ($n = 15$, $M = 3.67$, $SD = 1.29$) on the question "Current mining engineering graduates have demonstrated sufficient understanding of the overall mining operation" than their counterparts ($n = 13$, $M = 4.85$,

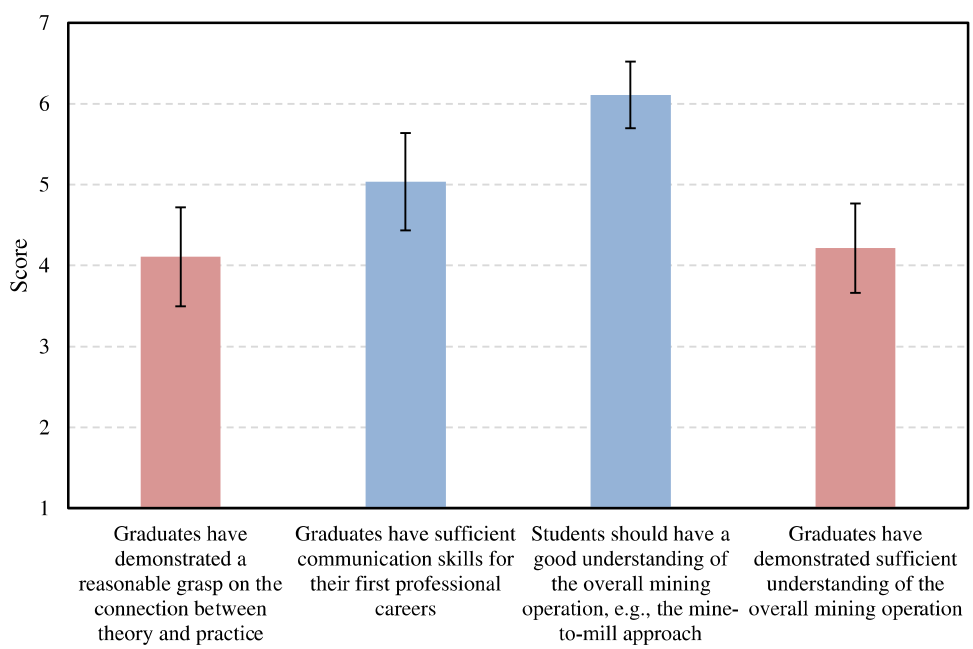

Fig. 3 Qualifications of graduates derived from the overall program. Scores of 1 = strongly disagree, 4 = neither agree nor disagree, 7 = strongly agree. Error bars show the 95% CIs. Error bars show the 95% CIs. Orange bars have the lower limit lower than 4, which indicate areas require improvement

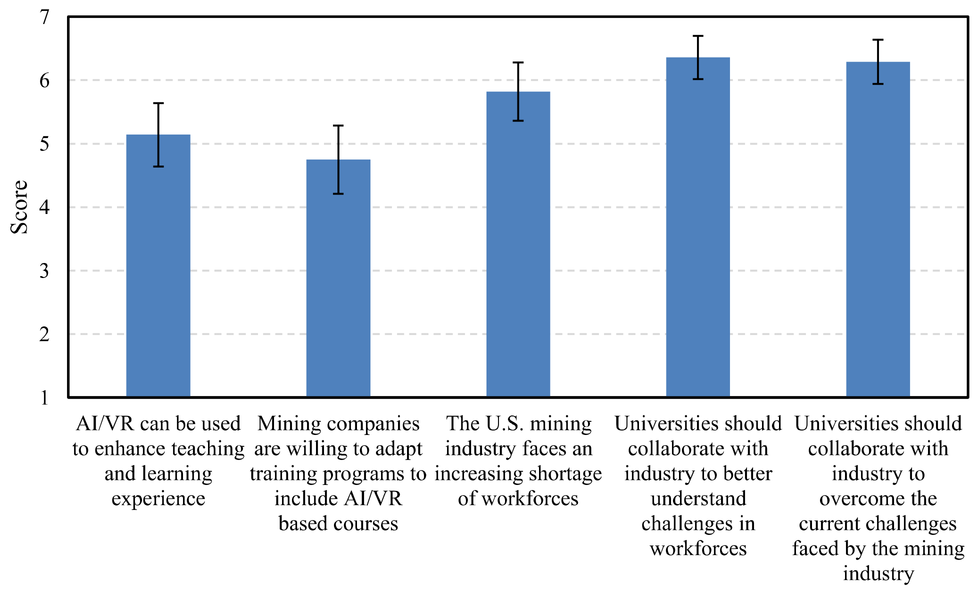

Fig. 4 Possibilities of applying artificial intelligence/virtual reality (AI/VR), shortage of workforces, and collaboration between universities and industry. Scores of 1 = strongly disagree, 4 = neither agree nor disagree, 7 = strongly agree. Error bars show the 95% confidence intervals

$SD = 1.35$), $t\,(26) = -2.37$, $p = 0.026$, $d = -0.90$. Significant differences are not found on the rest of the three questions (Table 2).

5.2 Results from Open-Ended Questions

5.2.1 Missing Qualifications of the Current Mining Engineering Graduates

Figure 5 shows frequencies of missing qualifications that were matched with seven criteria designed to reflect the student learning outcome. The frequencies of matched missing qualifications range from 2 to 5. Five missing qualifications mentioned by respondents can be addressed under criterion (2). One of the five respondents wrote, "Overall understanding of mining/metallurgy related equipment or extraction technologies." Four missing qualifications can be addressed under criteria (1) and (6). One respondent wrote the missing qualification under criterion (1) as "Understanding of metallurgical processes. Too many mining engineers view the mill/downstream processes as a 'black box'." An example of missing qualifications wrote by respondents that can be addressed under criterion (6) was "It seems the ability to apply comminution science is weak, and in some cases misunderstood."

All the missing qualifications that were matched with the criteria were provided by respondents who worked either in a mining/metallurgical operation company or a mining/metallurgical consulting company. One exception occurred under criterion (5). The missing qualifications within criterion (5) were provided by respondents who worked in a mining/metallurgical operation company, a mining/metallurgical

Table 2 Independent samples *t*-tests for qualifications of graduates derived from the overall curriculums

Question	Affiliated with a mining/metallurgical operation company	*M*	*SD*	*t*	*df*	*p*	*d*
Current graduates have demonstrated a reasonable grasp on the connection between theory and practice	Yes ($n = 15$)	3.87	1.64	−0.87	26	0.395	−0.33
	No ($n = 13$)	4.38	1.50				
Current graduates have sufficient communication skills for their first professional careers	Yes ($n = 15$)	5.07	1.49	0.11	26	0.912	0.04
	No ($n = 13$)	5.00	1.68				
Mining/metallurgical engineering students should have a good understanding of the overall mining operation, e.g., the mine-to-mill approach	Yes ($n = 15$)	6.20	1.01	0.49	26	0.630	0.19
	No ($n = 13$)	6.00	1.16				
Current mining and metallurgical engineering graduates have demonstrated sufficient understanding of the overall mining operation	Yes ($n = 15$)	3.67	1.29	−2.37	26	0.013	−0.90
	No ($n = 13$)	4.85	1.35				

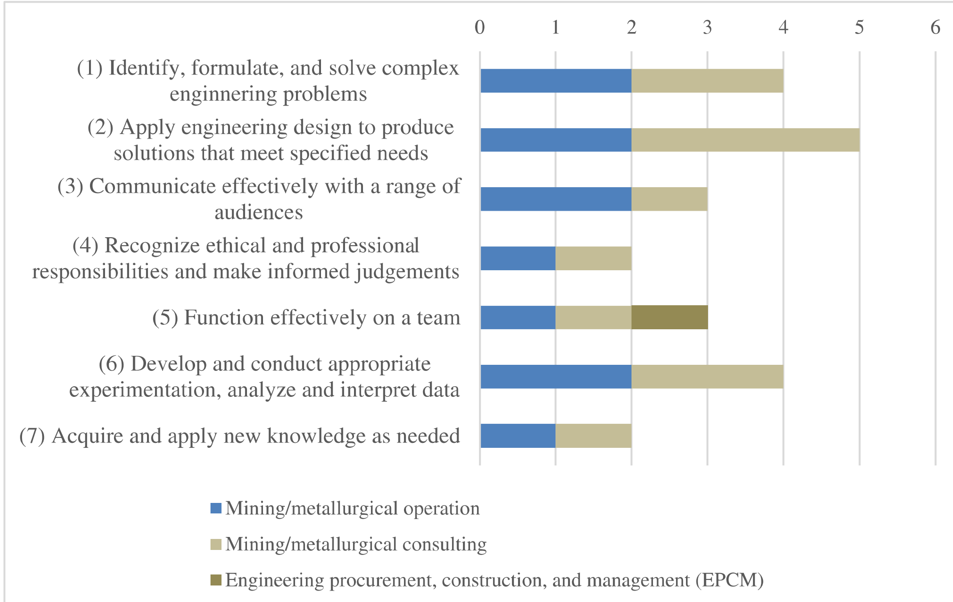

Fig. 5 Frequencies of missing qualifications

consulting company, and an engineering, procurement, and construction management (EPCM) company.

Figure 6 presents frequencies of missing qualifications that are under other categories. These missing qualifications were further grouped into three areas: sufficient experience in the field, develop skills and knowledge in general areas, and build confidence and interest. Frequencies of missing qualifications mentioned by respondents within these three areas ranges from 2 to 5. Five missing qualifications were categorized as "Sufficient experience in the field," two were "Develop skills and knowledge in general areas," and two were categorized as "Build confidence and interest." One missing qualification under the area of "Sufficient experience in the field" was written as "They are all book smart but cannot implement in the field." One respondent identified a missing qualification in "Develop skills and knowledge in general areas" as "Computing skills, mathematical and physical literacy." One of the missing qualifications under the area of "Build confidence and interest" was stated as "They should have strong pride in where they came from and who they are."

The five missing qualifications under "Sufficient experience in the field" were identified by respondents who worked in a mining/metallurgical operation company, a mining/metallurgical consulting company, or a mining/metallurgical equipment supplier company. The two missing qualifications

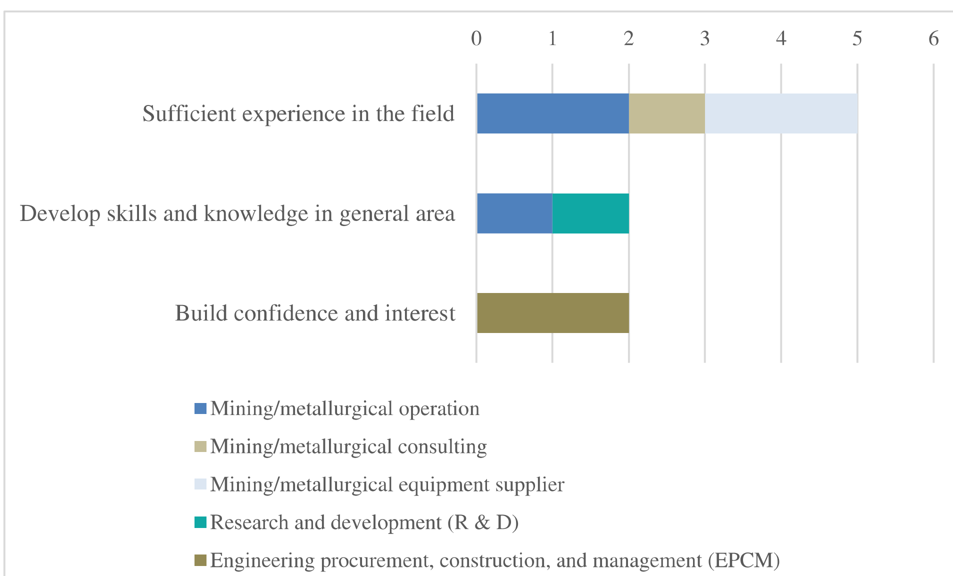

Fig. 6 Frequencies of missing qualifications under other categories

under "Develop skills and knowledge in general areas" were identified by respondents who worked in a mining/metallurgical operation company and a R & D company. The two missing qualifications under "Build confidence and interest" were identified by respondents who both worked in an EPCM company.

5.2.2 Desired Qualifications in the Next 5 Years

Figure 7 shows frequencies of desired qualifications in the next 5 years. Frequencies of matched qualifications ranges from 1 to 6. Six desired qualifications can be addressed under criterion (7)—"Acquire and apply new knowledge as needed." One example was "AI, machine learning, Big Data utilization." Four desired qualifications can be addressed under criterion (2). An example of this was "The graduates are getting the basics now. In the next 5 years, we would expect they are getting direction on where the mining industry is headed with regard to automation, digitalization, software development for autonomous mining, carbon footprint measurement and reduction, sustainability, and circularity." Three desired qualifications can be addressed under criterion (3)—"An ability to communicate effectively with a range of audiences." An example of this was written as, "You need to move away from the typical university technical writing and learn how to write for decision-makers, regulators, and the general public. Since that is not something typically understood well in academia, you need to reach out to the industry to find and teach this skillset to the students." None of the desired qualifications mentioned by the respondents can be matched to criteria (4) and (5).

The desired qualifications under criteria (2) and (7) were both identified by respondents who worked in a mining/metallurgical operation company, a mining/metallurgical consulting company, or a mining/metallurgical equipment supplier company. The desired qualifications under criterion (1) were identified by respondents who worked in a mining/metallurgical operation company and an EPCM company. The desired qualifications under criterion (3) were identified by respondents who worked in a mining/metallurgical operation company or a consulting company. The desired qualification under criterion (6) was identified by a respondent who worked in a mining/metallurgical operation company.

Figure 8 presents frequencies of desired qualifications in the next 5 years that cannot be matched with the seven criteria in Fig. 7. These desired qualifications were further grouped into three areas: sufficient experience in the field, connect with industry to understand research partnership and job opportunities, and other. The number of desired qualifications within these three areas ranges from 1 to 5. Five desired qualifications were categorized as "Sufficient experience in the field," two were categorized as "Other," and one was categorized as "Connect with industry to understand research partnership and job opportunities." One of the desired qualifications under the area of "Sufficient experience in the field" was written as, "Critical minerals processing experience. Critical minerals are those that are essential to the economy and whose supply may be disrupted." One respondent identified a desired qualification in the area of "Other" as "Very useful would be: advanced excel skills (macros, etc.), programming." The desired qualification under the area of "Connect with industry to understand research partnership and job opportunities" was stated as, "Better connected to the local, regional, national mining industry to more fully understand available research partnerships, job opportunities."

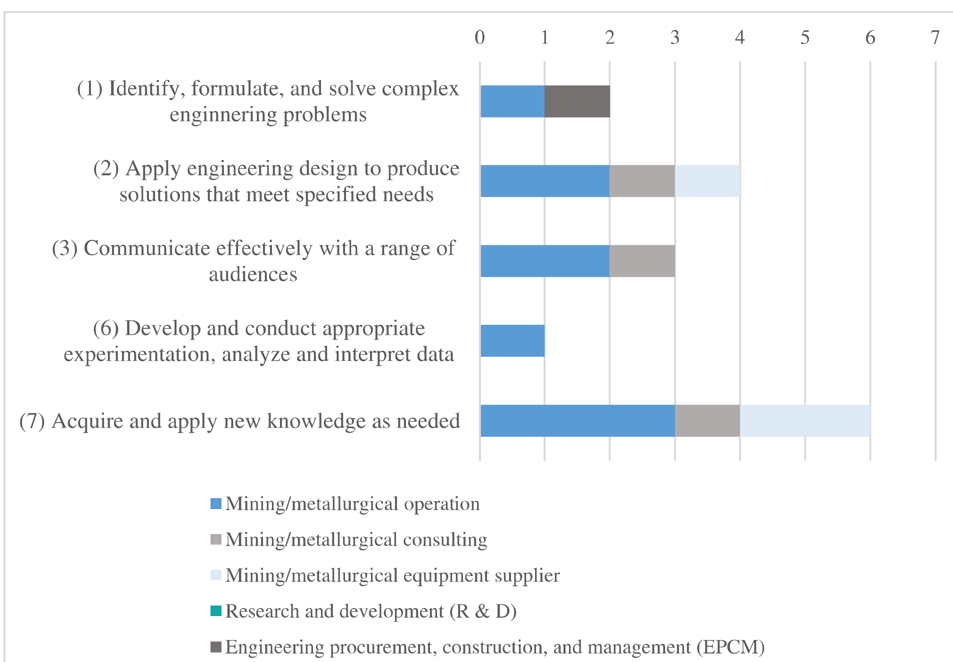

Fig. 7 Frequencies of desired qualifications in the next 5 years

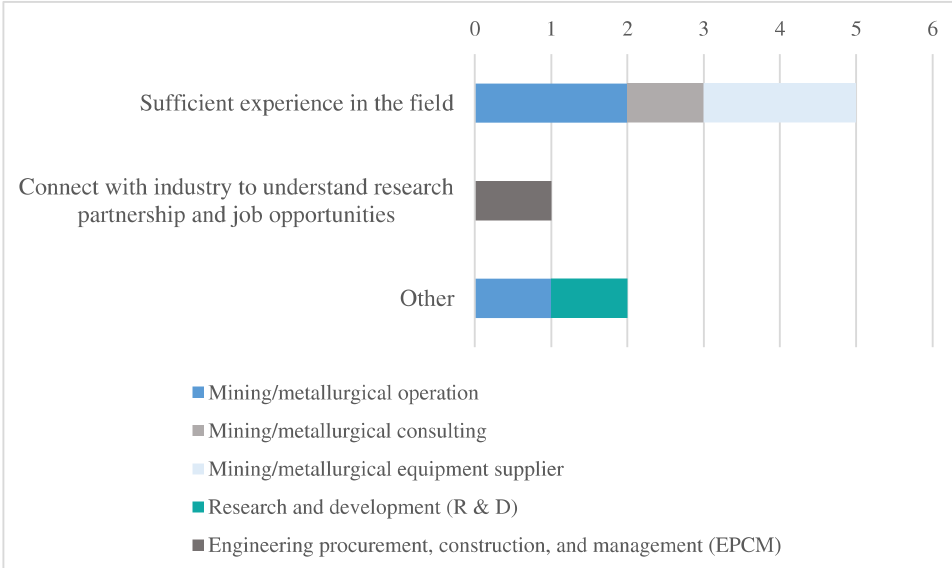

Fig. 8 Frequencies of desired qualifications in the next 5 years under other categories

The five desired qualifications under "Sufficient experience in the field" were identified by respondents who worked in a mining/metallurgical operation company, mining/metallurgical consulting company, or mining/metallurgical equipment supplier company. The two desired qualification under "Other" were identified by respondents who worked in a mining/metallurgical operation company and a R & D company. The missing qualification under "Connect with industry to understand research partnership and job opportunities" was identified by a respondent who worked in an EPCM company.

Based on our analyses of desired qualifications in the next 5 years, we suggested the projected emphases on criteria (1), (2), (3), (6), and (7). Because the question asked respondents to identify the desired qualifications in the next 5 years, it is not surprising that the greatest number of the desired qualifications was under (7)—"An ability to acquire and apply new knowledge as needed, using appropriate learning strategies." Similar to our findings on missing qualifications, respondents from multiple types of companies pointed out a need of sufficient experience in the field.

5.2.3 Recommendations to Enhance Future Mining Education

Figure 9 shows recommendations suggested by industry to enhance mining education. The recommendations were grouped into four areas: faculty hire and the focus of the school of mining, collaboration between industry and academia, a need of diversity, and more funding. The number of recommendations within these four areas ranges from 1 to 9. Nine recommendations were categorized as "Collaboration between industry and academia," four were "Faculty hire and the focus of the mining school," one was "A need of diversity," and one was "More funding." One of the recommendations under the area of "Collaboration between industry and academia" was written as, "More industry academia collaborations to bring out relevant solutions for the industry." One respondent suggested in the area of "Faculty hire and the focus of the mining school" as, "When hiring faculty to teach engineers, the emphasis should not be on research or other academic pursuits, but on practical engineering experience. Also, on choosing personalities that like to interact with students." The recommendation of "A need of diversity" was stated as, "I think creating diversity of the mining/metallurgy education is important as it is a very broad topic with many commodities involved." The recommendation of "More funding" was written as, "More funding for mining education."

The nine recommendations under "Collaboration between industry and academia" were identified by respondents who worked in all kinds of companies included in the study. The four recommendations under "Faculty hire and the focus of the mining school" were identified by respondents who worked in a mining/metallurgical operation company, a mining/metallurgical equipment supplier company, and an EPCM company. The recommendation under "A need of diversity" was identified by a respondent who worked in a mining/metallurgical consulting company. The recommendation under "More funding" was identified by a respondent who worked in a mining/metallurgical equipment supplier company.

5.2.4 Challenges that May be Tackled by New Technologies

Several respondents provided their feedback on forthcoming industrial challenges that have the potential to be tackled by new technologies in the coming years. Table 3 presents these comments by respondents' companies.

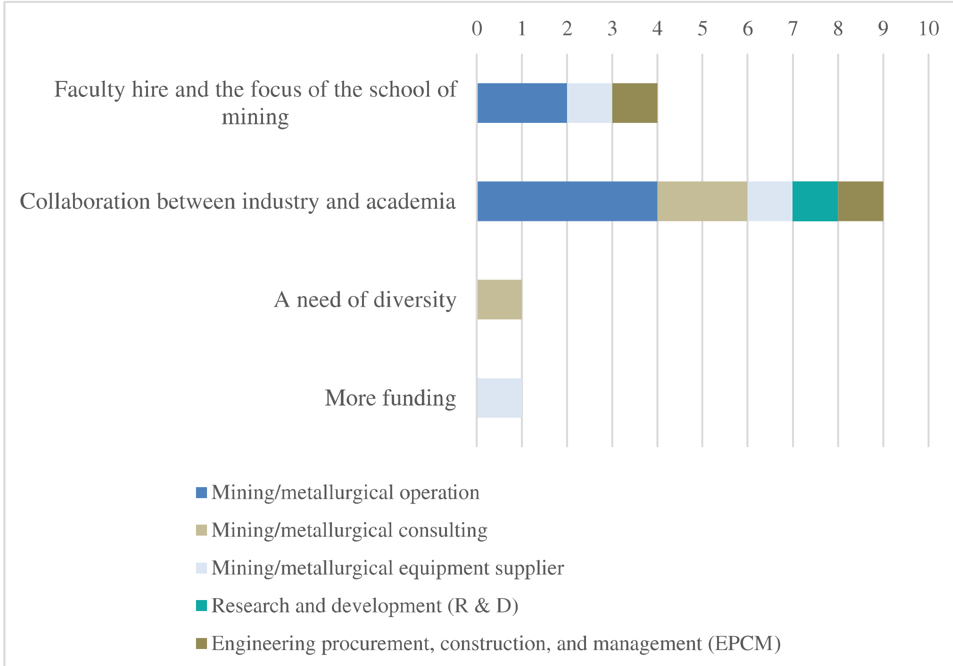

Fig. 9 Frequencies of recommendations for enhancing mining education in each area

6 Discussion

We present findings from our survey to understand the industry perspective on the U.S. metal mining engineering education. In this section, we summarize our findings from the survey and answers to the four research questions. Limitations of the study are also discussed. Based on the progress made in other countries and our survey findings, we provide four recommendations for future improvement.

In general, industry participants perceived increasing shortage of workforces in the U.S. mining industry, which is consistent with the quantity issue being reported in the literature [5–9]. Moreover, participants overwhelmingly agreed that universities should work closely with industry to better understand challenges in workforces and to overcome the current challenges faced by the metal mining industry. In fact, the involvement of industry in developing and improving mining education has been practiced in the other countries [6, 11, 17, 19], and in the U.S. through Accreditation Board for Engineering and Technology (ABET) [24] and Society of Mining, Metallurgy and Exploration (SME). The survey findings seem to suggest this area of collaboration can be further enhanced. Industry participants perceived that mining graduates were aware of challenges faced by industry. They also seem to conquer with the use of new technologies, such as AI/VR, to improve student learning and are willing to adapt their training programs to include these technologies. This is in line with the current trend in using emerging technologies to enhance mining education [6, 15, 18]. Although the

Table 3 Challenges that may be tackled by new technologies in the coming years

Respondents' company	Comment
Mining /metallurgical operation	• Big data management, modeling, and simulations • Environmental remediation/water treatment to continue to operate within permit conditions. Declining ore grades require continuous optimization to maintain economic viability. New technologies that address this challenge are always welcome • Standard mining operations in extreme adverse environments, e.g., high rock temperatures, extreme climactic cold • Arsenic locked preg robbing low grade ores
Mining/metallurgical equipment supplier	• New technologies for economically processing various low-grade ores and tailings, such as copper ore, phosphate, and rare earth, etc
EPCM	• The industry is faced with challenges and is in "constant" adaptation mode. A better relationship with the NV-based industry would help to drive research partnerships. Challenges include identifying resources (AI and other tech); metallurgy and extraction; closure and sustainability; changing reporting formats (ESG and beyond)
R & D	• Sorting small particles

study included a small number of industry participants, responses from these participants entail useful information towards improving the metal mining engineering education. Our answers to the four questions are presented below.

6.1 What Are the Required Qualifications a Mining Engineering Graduate Should Have to be Hired by the Mining Industry?

Most expected qualifications for mining graduates can be obtained through the current metal mining engineering curriculum. However, the survey also revealed a few missing qualifications desired for the future mining, indicating a quality issue in the current mining education that needs to be addressed. In addition, findings from our survey revealed that the industry expect graduates to have sufficient experience in the field as well as a good understanding of research partnership and job opportunities. This highlights the importance of promoting student internship programs and developing more enhanced collaboration between industry and academia to formulate solutions for the limited field experiences among current graduates.

6.2 What Are the Areas for Improvement in the Current Mining Engineering Education at Higher Education Institutions?

We identified five specific areas that require improvement:

- engineering sciences underlying the mining methods,
- mining design experience,
- mining feasible study,
- connection between theory and practice, and
- understanding of the overall mining operation.

Most responses to the question "In your opinion, what qualifications are missing from your current new mining graduate hires?" can be categorized into the seven criteria for evaluating student outcome shown in Fig. 5. The top three most fluently mentioned are criterion 1 (i.e., identify, formulate, and solve complex engineering problems), 2 (i.e., apply engineering design to produce solutions that meet specific needs), and 6 (i.e., develop and conduct appropriate experimentation, analyze, and interpret data). Similar to the required qualifications, industry respondents perceived improvements should be made to help mining graduates to obtain sufficient experience in the field.

Two of the survey participants who were affiliated with an engineering procurement, construction, and management company specifically indicated confidence and interest as missing qualifications. These findings echo Hayes' (2019) suggestions for the potential actions by universities to develop future workforce in mining [5]. His suggestions include (1) developing flexible entry and pathways into mining programs, (2) articulating clear and exciting career pathways and opportunities for graduates, and (3) promoting and marketing a positive view of the future of the mining industry. These suggestions can be considered to build student confidence and interest [5].

6.3 What Are Recommendations Proposed by Industry for Promoting Mining Engineering Education?

Recommendations proposed by industry for promoting mining engineering education fall into four different areas: (1) faculty hire and the focus of the school of mining, (2) collaboration between industry and academia, (3) a need of diversity, and (4) more funding. Among these four areas, collaboration between industry and academia was not only the most frequently mentioned area but also was mentioned by participants from all types of mining companies.

In our review of the proposed strategies for improving minding education, we also identified efforts made to invite industry to provide feedback on reforming mining engineering undergraduate curriculum (e.g., Hitch [11]). Furthermore, some suggested mining programs to reduce the time students spend in universities in lieu of field experience in mining companies (e.g., Spearing et al. [19]; Zhong [17]). One recently developing master's program goes beyond the traditional collaboration between universities and industry and is developed as an interdisciplinary, industry-driven master's program [6]. Multiple universities, industry companies, and research institutions across different countries in Europe are partners of this project. This is line with our industry respondent's suggestion on the need for diversity. Regarding issues with funding, a mining education fund model that requires government, mining companies, equipment manufacturers, and mining contractors to contribute was proposed to fund innovative research and teaching in autonomous mining in Ghana [18].

6.4 Do Different Sectors in Mining Industry Have Different Perspectives on the Required Qualifications that a Mining Engineering Graduate Should Have?

Consist with the literature [25], our survey findings revealed a significant difference on the perceived understanding of the overall mining operation among current mining engineering graduates between participants who were affiliated with mining/metallurgical operation companies and participants who were not affiliated with mining/metallurgical operation companies. Likewise, a few written responses were provided by specific companies but not others, such as the missing qualification of confidence and interest in mining.

This implies that some qualifications and expectations may be unique within different mining companies. It also suggests that participants from different mining companies may have their unique perspectives on strategies for improving future workforce. Thus, taking into consideration industry's perspective for improving mining education should invite representatives from different types of companies to have a holistic view of expectations from industry.

6.5 Limitations and Future Directions

As with any survey study, findings and recommendations presented in this paper are based on the specific survey respondents recruited in the study. While the findings entail useful information from an industry perspective, the respondents from the industry may not be familiar with the challenges because of the educational requirements. In the US, a curriculum must comprise of around 130 credits to establish an educational foundation for mining and metallurgical engineering undergraduate programs. The curriculums are designed to cover a wide range of topics so that students can graduate with a diverse set of skills. Moreover, the program needs to complete within about 4 years, which is a very difficult assignment. Also, some specialty skills which have been identified as areas for improvement cannot be achieved during undergraduate study but need graduate level education. It is very likely that the respondents of this survey representing practicing professionals are not aware of this complexity, therefore giving low satisfactory comments.

It should be emphasized that the US has a certification mechanism, that is ABET, for continuous improvement in mining engineering education. The Engineering Council for Professional Development (ECPD), which was the former of ABET, was established in 1932. Over the next 87 years, the certification program was expanded and universally adopted by all US mining and metallurgical program until 1980 the certification process was renamed ABET. One of the requirements of ABET certification is direct industry involvement in curriculum development and improvement. While ABET has established systematic criteria to include industry for continuous education improvement, the findings from this study provide some additional perspectives. On that, the following supplementary actions may be considered: (a) inviting members of advisory boards of the 14 US mining universities to distribute similar surveys to their professional networks, (b) conducting focus group interviews with faculty members and students at mining universities to understand challenges and potentials for improving mining education, (c) conducting interviews with employees from different mining companies to gather their ideas for enhancing mining education, and (d) examining the effectiveness of integrating emerging technologies, guided with pedagogical theories, on improving mining education.

7 Our Recommendations

Based on the progress made in other countries and findings from our survey, we provide the four additional recommendations to the existing certification mechanism for improving the U.S. metal mining education programs:

(1) involving more stakeholders, such as students, faculty members, staff in mining related research institutions, and industry, in reforming mining education programs;
(2) reinforcing more or mandatory field experiences as a key part of mining engineering education programs;
(3) developing a much closer collaboration between academia and industry;
(4) integrating emerging technologies, guided by pedagogical theories (e.g., Community of Inquiry, Garrison & Arbaugh [26]) to prepare for future mining workforce.

A close collaboration between academia and industry should allow industry to inform universities the current trends and needs in industry. Strategies for mining students to acquire more field experiences and build confidence and interest should be developed through collaboration. At the same time, industry may play a role in co-determining the focus and new faculty hire in the mining department/schools.

Potentials for using emerging technologies (e.g., AI/VR) in enhancing mining education are acknowledged by industry. Yet to effectively integrate these technologies in teaching and training, educators have to design learning tasks according to intended learning outcomes, and learning theories. For instance, the community of inquiry (CoI) framework was proposed to illustrate that a successful e-learning experience in the twenty-first century occurs through the interaction of cognitive presence, social presence, and teaching presence [27]. When the CoI framework is used to design a VR learning environment, educators need to design an environment that promotes the three presences and helps learners to learn through active participation and shared meaning-making. Specifically, cognitive presence is the extent to which learners are able to construct and confirm meaning through sustained reflection and discourse [28]. Social presence refers to the ability of learners to project their personal characteristics into the learning community, thereby presenting themselves as "real people" [29]. Teaching presence is "The design, facilitation, and direction of cognitive and social processes for the purpose of realizing personally meaningful and educationally worthwhile learning outcomes" [30]. We emphasize that a successful technology integration requires a critical examination of the affordances of the technology and strategical utilization its affordances to optimize learning outcomes in a specific learning context.

Appendix

Current university mining/metallurgy education survey—perspectives from mining company

The mining industry of today has evolved regarding both the challenges and the technological advances used to drive success. However, the current university mining education remains almost the same as decades ago. This survey intends to assess the qualifications of current mining graduates and identify areas of educational improvement. This survey will take about 10 min of your time

Please rate the degree to which you disagree or agree with the following statements

1. **Mining** current engineering graduates are prepared with the following qualifications to start their professional careers:

a Mining methods such as those used in mine planning, design, operation, and closures.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

b Mine design in underground and surface mines.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

c Engineering sciences underlying the mining methods, including thermodynamics, electrical circuits, hydraulics, and strength of materials.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

d Mining design experience.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

e Mining feasibility study.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

2. **Metallurgical** current engineering graduates are prepared with the following qualifications to start their professional careers:

a Mineral processing, such as comminution, flotation, magnetic separation, gravity separation, etc.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

b Engineering sciences underlying the mineral processing techniques, including physics governing particle separation, and chemistry for flotation.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

c Extractive metallurgy, including hydrometallurgy, electrometallurgy, and pyrometallurgy.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

d Engineering sciences underlying the extractive metallurgy, including thermodynamics, advanced chemistry, and heat and mass transfer.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

e Metallurgical flowsheet design, control, modeling, and optimization.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

3. Current graduates have demonstrated a reasonable grasp on the connection between theory and practice.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

4. Current graduates have sufficient communication skills for their first professional careers.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

5. Mining/metallurgical engineering students should have a good understanding of the overall mining operation, e.g., the mine-to-mill approach.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

6. Current mining and metallurgical engineering graduates have demonstrated sufficient understanding of the overall mining operation.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

7. Mining and metallurgical engineering graduates are aware of the current challenges faced by the mining industry in the areas of:

a Decreased ore grade requiring more sophisticated mining and metallurgical operations.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

b Growing challenges for tailing management.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

c Increasing responsibilities for sustainability and environment.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

8. Artificial intelligence/virtual reality can be used to enhance mining teaching and learning experience.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

9. Mining companies are willing to adapt their training programs to include artificial intelligence/virtual reality based courses.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

10. The U.S. mining industry faces an increasing shortage of workforces.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

11. Universities should collaborate with industry to better understand the challenges in the mining workforces.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

12. Universities should collaborate with industry to overcome the current challenges faced by the mining industry.

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

Please tell us about your role at your company and your company

13. Which one of the following best describes your role at your company?

    a Junior mining/metallurgical engineer
    b Intermediate mining/metallurgical engineer
    c Senior mining/metallurgical engineer
    d Engineering manager/supervisor
    e Executive/senior management
    f Health and safety specialist
    g Environmental specialist
    h Geologist
    i Others (please specify)

14. What one of the followings best describe the nature of your company?

    a Mining/metallurgical operations
    b Mining/metallurgical equipment supplier
    c Mining/metallurgical consulting
    d Engineering procurement, construction, and management (EPCM)
    e Laboratory testing
    f Others (please specify)

Please type your responses to the following five questions

1. In your opinion, what qualifications are missing from your current new mining graduate hires?
2. What qualifications would you expect from the mining/metallurgical engineering graduates in the next five years?
3. Does your operation have any challenges, which currently cannot be solved but have the potential to be tackled by new technologies in the coming five or more years? Please list such challenges and potential new technologies.
4. What software package does the company prefer for training and operation purposes?
5. Do you have any recommendations that can help the universities to enhance mining education?

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Data Availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Conflict of Interest The authors declare no competing interests.

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