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Validation of a Senior-Level Chemical Engineering Laboratory Course Technical Report Rubric that Aligns with Industry Expectations*

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A challenge instructors face is developing and accurately assessing technical communication skills to ensure students can apply and transfer the skills from the academic context into the context of engineering practice. By intentionally balancing teaching transferrable communication skills relevant to engineering practice and evaluating student understanding, engineering educators can foster competence and prepare students for the expectations of their professional careers. This study addresses two questions: (1) how can chemical engineering instructors reliably and consistently assess student communication skills, and (2) are instructor expectations aligned with those of practicing engineers? The use of well-designed rubrics is important for setting clear expectations for students, providing constructive feedback, and in team taught courses, grading consistently. This study discusses how a rubric for assessing technical communication skills in senior-level chemical engineering laboratory reports was validated and demonstrated reliability across five chemical engineering instructors. Additionally, five industry partners evaluated student reports for comparison to instructor rubric scores. Expectations and perceptions of the quality of student work align between instructors and practicing engineers, but practicing engineers prioritized safety and abstract clarity, while instructors prioritized the students' abilities to interpret results and draw conclusions.

Keywords: lab reports; industry; rubrics; chemical engineering; multi-instructor

1. Introduction

Professional skills such as communication are highly valued within the engineering profession [1, 2], as reflected by the key chemical engineering ABET outcome for engineering graduates of "an ability to communicate effectively with a range of audiences" [3]. Surveys indicate that practicing engineers spend a large portion of their time engaging in technical communication [4] and that technical communication training has been shown to correlate with increased success in the workforce [5]. Despite this, feedback from industry partners speaks to a lack of technical communication skills in engineering graduates entering the engineering profession [4, 5]. Engineering educators have long endeavored to effectively incorporate technical communication instruction and assessment into engineering curriculums [6, 7], with the goal to build skills in engineering students that are transferrable into their work. As research has shown, engineering communication is situated and rhetorical [2]. This presents a challenge for educators who are teaching within an academic context while simultaneously preparing students for an engineering practice where expectations may differ [4].

To address this challenge, the use of well-designed rubrics has been shown to help instructors effectively assess technical communication skills [8] and to serve as useful resources for students by making expectations explicit, which may result in improved performance [9] and possibly lower student anxiety [10, 11]. In addition, rubrics may be used as diagnostic tools, helping to identify gaps in student knowledge and as vehicles for effective feedback [12]. Previous literature has presented rubrics for scoring undergraduate engineering work based on group presentations [13], design projects [11], and soft skills in general [14]. All of those rubrics have constructs based on communication with the goal of fairly assessing student work and providing students with a roadmap to success. While undeniably useful, rubrics do have limitations. Rubrics attempt to assign numerical values to perspectives on writing quality that are inherently subjective, meaning that varying interpretations of

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criteria could occur by different instructors [8, 15]. In engineering courses, technical skills are likely being assessed in parallel with communication skills, making design of the rubric criteria potentially more complicated [12, 16]. Careful consideration is necessary to minimize inconsistency of scoring, to accurately assess communication skills and align rubrics with the standards of engineering practice.

In the present study, a rubric was developed to assess technical communication skills demonstrated in a technical report written for a senior level chemical engineering laboratory course. The rubric was then validated for reliability among course instructors using a two-way mixed, consistency, average-measures intraclass correlation (ICC). In addition, practicing engineers from industry were tasked to score sample student work. Scores were compared between instructors and practicing engineers to evaluate whether expectations and perceptions of the quality of the student work were consistent.

2. Methods

2.1 Experimental Course

In the chemical engineering curriculum at Montana State University, students are required to complete ECHM 442: Unit Operations Senior Laboratory I and ECHM 443: Unit Operations Senior Laboratory II. The objectives of these senior-level laboratory courses are to provide students with hands-on experience with unit operations commonly found in industry, to develop their communication skills and require them to work collaboratively in teams. The curriculum does not include a technical writing requirement, and therefore, oral and written communication training occurs primarily through these courses, along with capstone design. Both courses are team taught, with one lead instructor who coordinates the course, gives lectures, grades any homework and supervises one of six experiments. The other instructors each supervise one of the other six experiments and complete all the grading for students performing that experiment.

In the semester prior to taking ECHM 443, students learn about technical writing and the structure and format of the required writing assignments as well as review statistics through a series of 10 lectures in the ECHM 442 course. The students also complete two well-defined laboratory experiments in groups of 3–5. Then, ECHM 443 course builds upon the foundation of ECHM 442, providing further technical communication instruction and practice. The experiments in the ECHM 443 course are also less well-defined, providing more opportunity for experimental design and agency in analysis. The course consists of three 50 min lectures that cover course format, schedule and structure, give instruction for peer feedback and provide instructor feedback on technical reports. Students, in groups of 3–5, perform two lab experiments related to fundamental chemical engineering unit operations. The available experiments include heat exchangers, a continuous stirred tank reactor (CSTR), an enzyme kinetics experiment, and a friction and fluid flow experiment. Each student group is assigned two of the experiment types to complete and performs the two experiment rotations on a 5-week schedule. Over the course of the 5 weeks, the group prepares a written experimental plan, orally presents the plan to their instructor for approval and performs the experiment. Then the students, individually analyze the data and write a technical report or executive memo. Students also provide peer feedback on rough drafts of the reports. Assignments for the course include two group experimental plans, two group oral presentations of the experimental plan, two individual technical reports, one individual executive memo and two instances of peer feedback.

2.2 Instructor Grading

Five chemical engineering instructors of the ECHM 442 and ECHM 443 senior-level chemical engineering courses were provided with four samples of student work, technical reports on the topic of heat exchangers. The samples of student work were randomly selected from the Spring 2019 ECHM 443 course. Work was selected from the Spring 2019 semester to remove any association by instructors to current students. This semester was also chosen as it occurred prior to the COVID-19 shutdown, which altered the structure of the courses. The technical report was approximately 8 pages long and is expected to include: a cover page, abstract, introduction/background/theory, objectives, methods, results and discussion, conclusions and recommendations, and appendices. Instructors were asked to score the reports using the ECHM 443 technical report rubric, which was developed in collaboration with the university's Writing Center [17]. The rubric had a maximum total score of 30 points and consisted of six constructs with point values ranging from 1-to-4 or 1-to-7 (partial rubric shown in Table 1). In addition, to help students better understand the point values, point values correspond to traditional letter grades, "A", "B", "C", "D" and "F" level work such as for a 1–4 scale the point values are 4 for "A" work, 3.5 for "B" work, 3 for "C" work, 2.5 for "D" work and 0 for "F" work. For each level, a detailed description of what was required to obtain the corresponding grade was explicitly included on the rubric.

Table 1. Technical report rubric constructs, maximum point value of each construct and explicit detailed description of "A" level work

	Construct	Max Point Value	Description for "A" work
1	Context and Purpose	4	Demonstrates a thorough understanding of who you're writing for and what you're trying to accomplish with the report. All information is relevant for the context of the report and connected to the overall objective.
2	Technical Content and Analysis	7	Uses appropriate, accurate and relevant content to demonstrate clear understanding of the objective as related to engineering concepts, experimental methods and results. Clearly demonstrates ability to interpret results and draw conclusions.
3	Organization and Formatting	4	The technical report follows the organizational structure taught. It includes all required components/sections and each component is complete and formatted correctly, including proper citation. Under the 8 page (not including references and appendices) limit.
4	Figures, Tables and Schematics	4	All schematics, tables, and figures are correctly formatted, labeled, cited, and contain accurate and meaningful information.
5	Precise and Concise Technical Writing	7	The technical content is communicated clearly and succinctly with short and simple sentences. Precise and accurate technical language is readily understood by the intended audience. Sentences flow smoothly, are structurally correct and convey the intended meaning without wordiness so that the reader understands what was done.
6	Language Execution	4	Skillfully communicates using correct grammar and spelling with little to no distracting errors that interfere with reader understanding.

2.3 Instructor Inter-Rater Reliability (IRR)

Inter-rater reliability (IRR) was assessed using a two-way mixed, consistency, average-measures intraclass correlation (ICC) for each of the six constructs on which students were rated. The ICC is a descriptive statistic used to assess the level of consistency in ratings from two or more raters on the same construct across participants. The ICC works well with multiple raters who have used ordinal data for their ratings. The ICC can range from 0, random agreement, to +1.0, perfect agreement, with higher ratings indicating higher consistency among raters. For example, a rating of 0.80 would indicate that 80% of the variance among raters was due to true consistency among raters, and 20% was due to unexplained error.

2.4 Industry Grading

Industry participants were recruited to evaluate whether instructor expectations aligned with those of practicing engineers. The authors reached out to members of their departmental advisory board and five agreed to participate in the study. Participants were chemical engineers at various stages in their career and working in sectors ranging from energy (WBI Energy) to oil and gas (Cenex, Conoco Phillips), semiconductors (Micron) and materials science (3M Corp.). One participant was recently retired, three were senior level managers and two were process engineers. The five industry participants were provided four technical reports, three of which were the same as the instructors and one alternative report. The replacement of one report was made due to the high level of complexity in the instructor-graded report and therefore, was replaced with a more typical report. While the replaced report was not graded as part of the instructor validation, it was graded by five chemical engineering instructors at a later date. A document was also provided that described the course context, assignment context, objective of the technical report, and a brief refresher on heat transfer theory, which was the topic of the reports. The following feedback guidelines were also provided that were adapted from Sheffield et al. [16]:

- (High A work) Work earning this score is ready to be passed on to a real client. In every way, it meets audience needs. Major points are clear and well supported with evidence; technical content is correct. Document is formatted and organized to guide to major points. Clear and interesting visuals and prose contribute to professional-level quality.
- (A/A–) Work earning this score is strong and all technical content is correct. If I were your supervisor on an internship, I'd suggest minor changes before sending it on to a real client. Those changes might include slight changes to prose, visuals, or formatting to increase clarity and readability. The suggestions are truly minor, and if the document were sent on without the requested changes, I wouldn't be too concerned. None of the errors are so large that they would affect our company's or your relationship with the client.
- (B+/B) Work earning this score is good. If I were your supervisor on an internship, I'd consider this a strong draft but suggest changes before sending it on to a real client. Either because of

Table 2. Example of the scoring table that the industry participants completed for each report

Student 1	Grade based on Guidelines above:	
Comments regarding the quality of writing (i.e., what was good, what needs to be improved).		
What overall feedback would you provide the student?		

severity of a single issue (perhaps errors or missing evidence for technical content), or significant issues with prose, I would be concerned if this document went to a client without those changes made.
- (B–/C+) Work earning this score shows some promise, but it lacks much-needed polish and/or includes technical errors. If I were your supervisor on an internship, I would require substantive revision to the majority of the document before it could be passed on to a client. Though evidence of good ideas and/or solid engineering work is present, I am certain that a client would be too distracted by the many problems and/or technical errors to form a positive impression of you or our company.
- (C/C–) Work earning this score requires significant revision before it can be passed on to a real client. These changes include improvements in clarity and readability as well as in major content (perhaps content is missing, unclear, or wrong). I would panic if this document were sent directly to a client without significant revision, as I believe it could affect our company's relationship with the client.
- Scores lower than C– are uncommon (and usually the result of incomplete work).

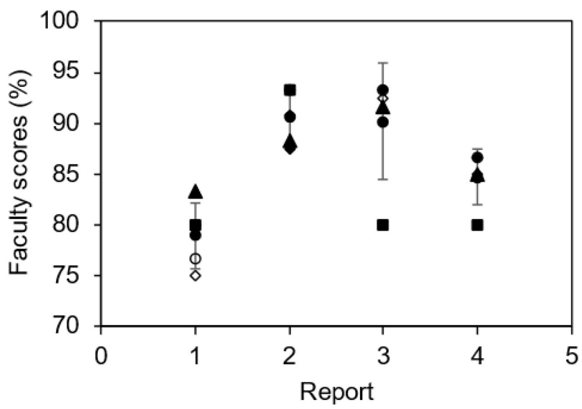

Fig. 1. The overall scores for four reports for each of the five instructors (as indicated by different symbols). Also shown are the average scores across all instructors for each report (●) and error bars represent standard deviations.

Table 3. Averages and standard deviations of report scores graded by instructors

Report	Instructor Average Scores (%)	Instructor Standard Deviation
1	79.0	3.2
2	90.7	2.7
3	90.2	5.7
4	84.7	2.7

For the industry participants, to simplify the grading process and reduce grading time they were given a more general score sheet (Table 2) asking for a letter score rather than scoring with the rubric. Then, in order to compare industry partner scores to instructor scores, the letter grades were converted to numerical scores using standard percent to letter grade conversions (e.g., A = 95, A/A– = 93, A– = 91, B+ = 89, etc.) for analysis.

3. Results and Discussion

3.1 Instructor Scored Reports (Rubric-based)

To assess the quality of student work, five instructors graded four reports using a rubric consisting of six constructs (Table 1). All instructors had prior experience teaching chemical engineering laboratory courses with technical report assignments. As can be seen in Fig. 1, instructor scores were largely consistent, approaching or within standard deviations for reports 1, 2, and 4 of less than 3.5% (Table 3). Report 3 had a higher standard deviation of 5.7%, resulting from one instructor grading the report significantly lower than the other three graders, which is shown as the square in Fig. 1.

To further explore report 3, Fig. 2 shows the points given for each rubric construct with each marker type representing a different instructor (other than the filled circle, which is the average score). It can be seen that the instructor represented by the square gave lower scores for three of the constructs. The square grader scored significantly lower for constructs 2 (Technical Content), 5 (Precise and Concise Technical Writing), and 6 (Language Execution). During a discussion meeting that followed the scoring, this instructor (square) felt that report 3 contained extraneous information and was missing necessary analysis. This decreased the scores in both Technical Content and Concise and Precise Technical Writing categories relative to the other instructors (Fig. 2). Due to the report score being 30 points, each point is equivalent to 3.33 percentage points. Since that grader was approximately 3.8 points below the average of the other instructors, that resulted in an over 12% lower overall score.

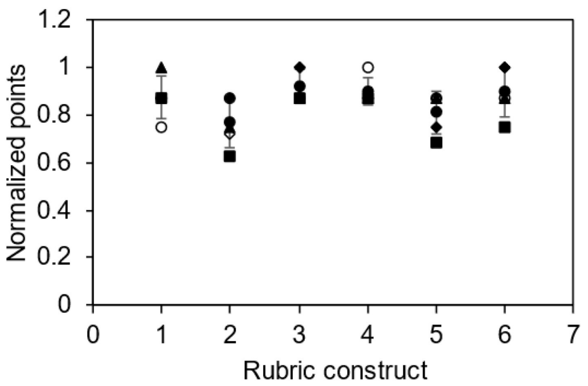

Fig. 2. Report 3 scores for each individual rubric construct (as defined in Table 1) for each instructor (correspond to same symbols as in Fig. 1). Also shown are the average scores for each construct (•) with error bars representing standard deviations.

Table 4. ICC on scores for the four randomly selected student sample technical reports graded by five instructors

Rubric Construct	ICC Value	Rating
Context and Purpose	0.79	Excellent
Technical Content and Analysis	0.63	Good
Organization and Formatting	0.75	Excellent
Figures, Tables and Schematics	0.61	Good
Precise and Concise Technical Writing	0.94	Excellent
Language Execution	0.55	Fair
Overall Score	0.90	Excellent

To further explore the consistency of grading between instructors, inter-rater reliability (IRR) was assessed where intraclass correlations (ICCs) of less than 0.40 are considered poor, between 0.40 and 0.59 are fair, between 0.60 and 0.74 are good, and above 0.75 are excellent. Some caution must be used in interpreting the ICCs reported here mainly because only four reports were rated; however, the ICCs do provide a general sense of how consistent the instructors were. It was found with the exception of the Language Execution construct, the instructors provided good or excellent consistency in their ratings (Table 4). The high ICCs indicate that the instructors had a high degree of agreement and a minimal amount of error leading to consistent report scoring.

Although there was high agreement in other constructs, the Language Execution construct, which evaluates the grammar and spelling quality within the report, was rated as "fair." When looking at the scores between graders for this construct, Fig. 3 shows that overall, the grading was fairly consistent, with only the square instructor providing a lower score due to the perceived excessive information. Since the standard deviations only ranged from 0.01–0.10 for each report, the Language Execution construct was deemed acceptable.

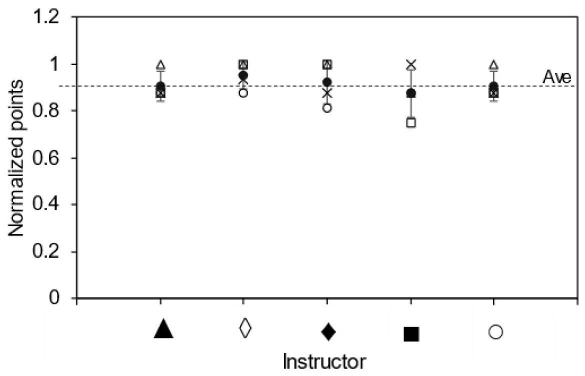

Fig. 3. The normalized points received for the rubric construct Language Execution by instructor (●, ▲, ◆, ■, and ○) for each of the four reports (○, □, △, and ×). Instructor averages are indicated by the filled circle (●) with an overall average of 0.91 indicated by the dashed line. Error bars represent standard deviations.

3.2 Industry Scored Reports (Letter grade-based)

To determine whether technical communication standards are similar for chemical engineering instructors and practicing chemical engineers, the latter were given four reports where reports 1–3 corresponded to the same reports numbered 1 through 3 that were scored by the instructors and discussed in the previous section. Report 4 was not provided to industry participants as it contained confusing, complex theory and likely would have imposed a significant time investment. Instead, industry partners were provided a report selected to be more standard, labeled report 4I. This report was not graded as part of the instructor validation of the rubric discussed above but was graded by chemical engineering instructors at a later date.

Fig. 4 shows the scores for each of the reports from the five industry participants, including the averages and standard deviations, which are also listed in Table 5. Report 1 had the highest variability with a standard deviation of 6.4% and scores that ranged from C/C– to B+/B. This is similar to the instructor scoring which ranged from a low of 75% (C) to a high of 83% (B). Reports 2 and 3 had lower variability with standard deviations of 4.3% and 4.8% respectively. Interestingly for report 3, one industry partner also highlighted the same extraneous information as one instructor (square grader) and correspondingly, gave a lower score (B+/B) than three of the other four industry participants (High A; A–; B+/B; A/A–). Note that some differences, particularly in standard deviation, would be expected as the industry partners used a letter-based grade system compared to the numerical rubric the instructors used. Overall, when combining the reports scored by both instructor and industry (reports 1–3), the industry partner scores were largely in agreement with instructor

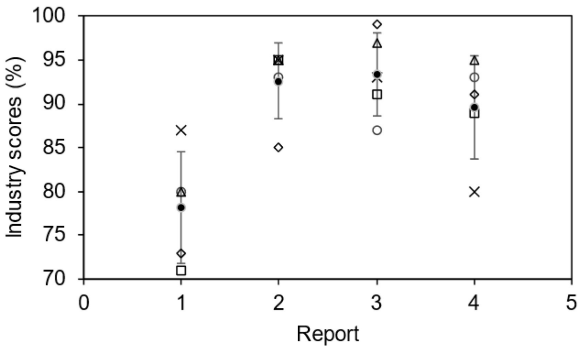

Fig. 4. The overall scores for reports 1–3 and report I4 for each of the five industry partners (as indicated by different symbols). Also shown are the average scores across all industry partners for each report (●). Error bars represent standard deviations.

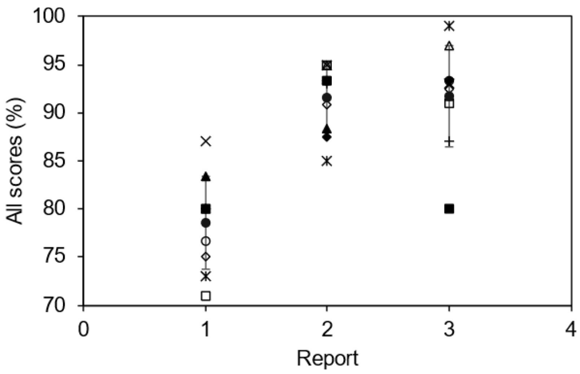

Fig. 5. The overall scores for reports 1–3 for both instructors and industry partners (as indicated by different symbols). Also shown are the average scores for each report (●). Error bars represent standard deviations.

scores (Fig. 5; Table 5), indicating that the expectations and standards of the chemical engineering instructors were in alignment with those of practicing engineers. Although overall scores were in alignment between instructors and the industry partners, further analysis was done on the comments provided by both to determine if the noted deficiencies were similar.

Two instructors provided detailed written feedback and all five industry partners gave some comments on reports 1–3. The general themes of comments were largely consistent, particularly between the instructors and then between the industry participants, although industry partners and instructors tended to focus on slightly different aspects (Table 6). In general, industry partners placed a high emphasis on the quality of the abstract, professionalism and on safety, while instructors focused more on technical writing, the results and analysis, and the technical content. Instructors did comment on the need for improved technical writing but did not use the word "professionalism." Industry participants noted that upper-level managers often do not read past the abstract, and hence, why there was more focus on it. Additionally, having good grammar and word selection "are important in building the trust of the reader in your technical abilities." Finally, safety was a theme overall for the industry participants as several, but not all, made comments regarding safety, either complimenting the safety considerations or recommending improvements. The instructors did not

Table 5. Average and standard deviations of report scores by instructors and industry partners and corresponding letter grades for reports 1–3, graded during the instructor rubric validation, and the report graded by industry and instructors outside of the rubric validation (4I)

Report	Instructor Average Scores (%)	Instructor Standard Deviation	Instructor Letter Grades	Industry Partner Average Scores (%)	Industry Partner Standard Deviation	Industry Partner Letter Grade
1	79.0	3.2	C+	78.2	6.4	C+
2	90.7	2.7	A–	92.6	4.3	A–
3	90.2	5.7	A–	93.4	4.8	A/A–
4I	84.9	2.1	B	89.6	5.8	B+

Table 6. Summary of the written feedback given by industry and instructor graders

Report	Industry Feedback	Instructor Feedback
1	• Poorly written abstract • Lacks professionalism • Would "panic if a report of this quality was sent to a client"	• Poorly written overall report • Technical writing needs improvement • Results lack interpretation
2	• Strong abstract, but could be more concise	• Abstract needs to include results interpretation
3	• Well-written • Contained excess information: "Less is more" and "scope creep," which could lead to necessary costs for client	• Needs a clear conclusion and recommendation • Contained superfluous details
I4	• Abstract needs improvement • Inconsistencies in the results • Incorrect word use • Excellent safety section; "sets the bar for how these subjects should be conveyed"	• Noted deficiencies in each section of the report • Abstract was weak • Lacked clarity in the results and discussion • Had technical errors

comment near as much on the safety section but felt that this was an important section to emphasize going forward.

3.3 Limitations

There are some limitations for this validation study. Although there were five raters involved in the rubric validation to determine the IRR of the rubric, the raters examined only four technical reports that were on the same topic in order to reduce the amount of topic reviewing that the industry partners needed to do. Ideally, more reports from different experiments would be used to determine if there are differences in report topics. One other limitation is that the industry partners did not use the rubric to grade the technical reports, but instead just assigned a letter grade that was converted to a percentage. Having the industry partners use the rubric could provide further validation that the rubric is robust although would require more time. Additionally, this rubric was only validated across instructors in two different chemical and biological engineering courses at one institution. Expansion to other courses, departments, and even institutions could provide insight as to whether this rubric would be of value for other courses.

4. Conclusions

This study sought to address two questions: (1) how can chemical engineering instructors reliably and consistently assess student communication skills and (2) are instructor expectations aligned with those of practicing engineers? A rubric was designed to assess technical skills, using a technical content and analysis construct, and communication skills using constructs that assess particular aspects of technical writing such as context and purpose and precise and concise technical writing. Instructor scores evaluating technical reports using the rubric were consistent between instructors as shown by the close ranging average scores, low standard deviations, and high ICCs. These rubrics could be utilized broadly in engineering laboratory courses with a technical writing component with minor adjustments to accommodate differences in course structure, disciplinary variations, and industry expectations in various cultural contexts. As instructor discussion about the scoring process yielded valuable insights on what instructors valued and why, an instructor 'training' or 'orientation' for new instructors or team-taught courses would be beneficial to ensure alignment of expectations and consistency of scoring. Such a training could include discussion on interpretation of rubric constructs, how to provide clear feedback tied to the rubric, and practice with the rubrics prior to the course.

In addition, expectations of quality were, on average, similar between instructors and practicing engineers, the industry partners. When looking qualitatively at comments, some differences emerged. Industry partners placed a high emphasis on the issue of safety and a concise, yet summative abstract while the instructors had a more holistic view, with an emphasis on interpretation of results, discussion and drawing of conclusions. Taking into account this knowledge, instructors should put more emphasis on the abstract and safety. Given the academic context and learning objectives of the course, however, instructors should still hold high standards for the students on technical analysis. Industry partners have an assumption of competence once a student has graduated, and focused less on the technical content, assuming it was accurate. As educators, it is our job to get students to that point of competency and to teach transferable communication skills relevant to engineering practice. This work provides insight into the necessity of balancing teaching within an academic context with preparing students for the practice of engineering. With the framework provided by the rubric, instructors could adjust the rubric to align with industry expectations within their context and also use the understanding gleaned from the validation process in instructor orientations to emphasize how to assess student skills through both the academic and industry lens.

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