Performance Assessment of EC-2000 Student Outcomes in the Unit Operations Laboratory

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Summary

The new ABET Engineering Criteria 2000 (EC-2000) describe eleven student outcomes which must be demonstrated by graduates of accredited programs. Many of these outcomes focus on professional engineering practice including an ability to design and conduct experiments; analyze and interpret data; identify, formulate, and solve engineering problems; function on multidisciplinary teams; communicate effectively; and use the techniques, skills, and modern engineering tools necessary for engineering practice. Each of these outcomes is best evaluated using some form of performance assessment where students are judged on their ability to complete the required task in a setting approaching authentic engineering practice rather than by traditional objective tests which focus on non-contextual recall of facts and closed-ended problem-solving.

This paper describes the process we followed to design and implement performance assessment in the unit operations laboratory including setting goals and objectives compatible with our departmental program objectives, defining appropriate student performance criteria, developing and testing a scoring rubric for laboratory written reports, deciding when and how often we assess, and determining how to evaluate the collected assessment data. Assessment results from our first pilot study are presented and discussed to illustrate the utility of the data obtained in improving the laboratory course and chemical engineering curriculum.

Introduction

Most of us are aware that traditional engineering courses overemphasize "plugging and cranking" on well-defined, close-ended, numerical problems at the expense of helping students become better critical thinkers and engineering practitioners. As a result, and in sharp contrast with other professions such as medicine and law, too few of our engineering graduates are capable of immediately practicing engineering when they leave college. Yet, industry expects to hire engineering graduates who "can go beyond the numbers" by understanding how technical results fit into a larger systems perspective, who can integrate knowledge to find new solutions to problems rather than relying on a traditional reductionist approach, who can deal with uncertainty and develop engineering judgment skills, and who can communicate the results of their work to many different audiences. [1,2] In short, they want engineers who can "think outside the academic box." In response to these expectations, many of the new ABET EC-2000 outcomes focus on professional practice including: (3b) "an ability to design and conduct experiments, as well as to analyze and interpret data;" (3e) "an ability to identify, formulate, and solve engineering problems;" (3d) "an ability to function on multi-disciplinary teams;" and (3g) "an ability to communicate effectively." [3] Student ability in each of these areas is best assessed using some form of performance assessment—a quantitative judgment of the quality of student work by experienced raters based on agreed-upon criteria. [4]

We believe that the unit operations laboratory provides an ideal setting to help chemical engineering students become better engineering practitioners and to assess their progress toward achieving this goal. At the Colorado School of Mines (CSM), we offer the laboratory course as an intensive six week summer experience designed to enhance and assess students' higher order thinking skills and knowledge of many aspects of chemical engineering professional practice including data collection and analysis, evaluation and interpretation of results to draw meaningful conclusions, team processes, and communication of technical results to a variety of audiences. The course structure allows us to collect rich performance assessment data on students' ability to apply classroom knowledge of unit operations to situations approaching the "real-world" including dealing with "noisy" data, overcoming equipment limitations, using statistics in a prudent way, comparing "real" data to theoretical and empirical models, and communicating complex results to a variety of audiences under significant time constraints.

As presently taught, the course relies heavily on a constructivist approach—that is, the cognitive theory suggesting that learners construct their own internal interpretation of objective knowledge based, in part, on formal instruction, but also influenced by social and contextual aspects of the learning environment and previous life experiences. [5] This view suggests that students "make their own meaning" of what they are learning by relying on mental models of the world, models that may be correct or may contain strongly held misconceptions. [6] Rather than acting as acknowledged authorities transmitting objective knowledge to passive students, laboratory faculty use coaching and socratic questioning techniques to help students understand complex technical phenomena by constructing mental models which reflect reality as perceived by acknowledged experts while minimizing models containing significant misconceptions. Use of constructivist pedagogies creates an ideal context for assessing students' abilities to complete authentic engineering tasks rather than relying on artificial examinations which emphasize non-contextual recall of facts and closed-ended problem-solving.

In this paper, we briefly describe the course structure, the process we used to create and validate a new performance assessment scoring rubric for written laboratory reports, and results of our pilot assessment work using the rubric.

Overview of the CSM Unit Operations Laboratory

To facilitate development of each student's engineering abilities in the unit operations laboratory course, supervising faculty place as much responsibility for the planning, execution, analysis, evaluation, and reporting of experiments on the students as possible. Each student performs a total of eight experiments in fluid mechanics, heat transfer, and mass transfer working in teams of two or three. Teams are randomly sorted from experiment to experiment so that students work with all their peers in the course and each student has the opportunity to serve as a "team leader" on several experiments. Since the students have received extensive team-building instruction and practice in previous CSM coursework, no explicit team-building work is required in the laboratory. Details of the course objectives and pedagogical structure have been reported. [7]

The afternoon prior to performing an experiment, each student team meets to become familiar with the general experimental objectives and safety guidelines provided by faculty supervisors, to study the equipment and how to measure and model its performance, to create a list of detailed experimental objectives, to develop an experimental design for data collection, and to decide what statistical analysis strategies will be used with the experimental data. Less than one page of written guidelines (including safety issues) is typically available for each experiment; faculty supervisors act as coaches or mentors to the teams but do not portray themselves as authority figures. Early on the morning the experiment is scheduled, each student team presents the results of the "prelab" preparation to a supervising faculty member who questions members of the team on all aspects of the experiment including background theory; working equations; data collection; measurement errors and data reproducibility; and data analysis and evaluation.

After successfully passing the prelab oral "exam," each student team controls its own destiny in the laboratory and operates without input from faculty supervisors or teaching assistants (except for potential safety issues). Students make all decisions about ranges of data to collect, about the amount of data to collect, and about conducting reproducibility runs.

With data in hand, the team begins the process of data analysis, comparison of results with theoretical predictions or accepted correlations, and statistical error analysis. This is an intense time for the team—they must either prepare and deliver a 20 minute oral presentation describing their work one day after completing the experiment or must submit a draft written report five days after completing the experiment. In either case, they must complete calculations, develop appropriate correlations of engineering parameters such as friction factors or heat transfer coefficients, prepare figures and tables of results, develop error propagation and statistical analyses, provide logical explanations for any deviations of their results from expected values, and develop overall conclusions based on evaluation of their work.

Students produce four oral and four written reports on experiments completed during the course. Oral presentations are attended by other students in the course and by one or more faculty supervisors; presenters are expected to focus largely on the conclusions drawn from their results and reasons for any obvious discrepancies from expected trends. Once again, faculty use socratic questioning to probe for evidence of analysis, synthesis, and evaluation by student teams. Each written report is submitted first in draft form for review by the faculty supervisor and a technical communication specialist. Draft review meetings are then held with individual student teams to provide feedback and discuss remaining difficulties in technical and rhetorical content before the final version of the report is submitted for grading.

Implementing Performance Assessment in the Unit Operations Laboratory

As the CSM chemical engineering department faculty began developing our assessment and evaluation plan to meet ABET EC-2000 requirements, we recognized that the learning objectives and pedagogical methods associated with the unit operations laboratory experience make the course an ideal setting to assess how well our students can actually apply their knowledge of unit operations, statistics, communications, and teamwork to the operation and analysis of laboratory equipment. While our entire assessment plan consists of three goals and fourteen objectives, we agreed that the following educational objectives were the appropriate ones to assess in the course:

- Students will be able to apply knowledge of unit operations to the identification, formulation, and solution of chemical engineering problems (ref. ABET 3a, 3e).

- Students will be able to design and conduct experiments of chemical engineering processes or systems and they will be able to analyze and interpret data from chemical engineering experiments (ref. ABET 3b).

- Students will demonstrate an ability to communicate effectively in writing (ref. ABET 3g).

Once these objectives were identified and agreed upon, we began considering possible assessment tools for measuring each objective including examinations, faculty and student surveys, portfolios, interviews, focus groups, and performance assessment. While we eventually hope to expand the number of instruments used, we are initially focusing on assessing written laboratory reports because faculty are already comfortable evaluating students' written work and because we believe we can reliably assess all three objectives listed above using well-designed and tested scoring rubrics.

After deciding to collect and assess written reports, we had to determine what evidence would demonstrate that students had met the objectives and how the evidence would be evaluated. This required developing articulated levels of performance against which to measure student achievement and organizing the performance levels into a scoring rubric. Greene [8] has listed the steps required to design and test a reliable rubric instrument:

- Determine what objectives the rubric will be used to assess.
- Determine what student work will be assessed with the rubric.
- Determine an appropriate rating scale for scoring student performance.
- Draft the rubric using samples of student work at all performance levels as a guide.
- Test the rubric on student work (preferably using double blind-scoring to evaluate the instrument's reliability.)
- Revise the rubric language until inter-rater reliability meets faculty expectations.

Based on a review of many rubrics, we initially developed a scoring rubric with three levels of articulated performance: 1) “exceeds standards,” 2) “meets standards,” and 3) “does not meet standards.” We then drafted language describing student work at each of these levels for each of the three objectives being assessed. However, when we used the draft rubric to score student reports, we quickly found that three scoring levels was insufficient to differentiate between acceptable and unacceptable student performance (virtually none of the reports exceeded the standard or didn’t meet the standard, so almost every report was judged to “meet standards”—not a very useful result to help improve the course and chemical engineering curriculum, which of course is the ultimate reason to assess student work).

We also found that the use of the term “standards” in our rubric seemed to denote for some faculty the notion of a “minimum standard” which then erroneously implied some sort of “lowest common denominator graduation requirement” that absolutely every student would have to achieve. These examples served to remind us that we had to be extremely careful in our choice of language used in scoring rubrics we developed. We eliminated these difficulties by expanding the rubric to include four levels of articulated performance (“exemplary,” “proficient,” “apprentice,” and “novice”) and avoiding use of the term “standard.”

After about three iterations of rubric testing and redrafting by the four-member departmental assessment committee, we were able to design an instrument that is easy to use (a typical 15-20 page lab report can be scored in 5-7 minutes), reliable (based on blind-scoring of sample rubrics by multiple raters), and descriptive of expected student performance. Table I shows the current version of the rubric we are using to evaluate unit operations laboratory reports. We also plan share the rubric with students in future sections of the unit operations laboratory course to help them better understand our expectations for satisfactory and superior performance.

Once the rubric instrument was developed to our satisfaction, we conducted a “norming” session to make sure we could achieve and document inter-rater reliability when assessing laboratory reports. Four sample laboratory reports were independently scored by all four assessment committee faculty members using the rubric shown in Table I. Results from this work are summarized in Table II and show that the range of scores for 10 of 12 scored objectives (4 reports with 3 objectives per report) agreed within 1 point, our self-imposed reliability criterion. We consider this level of agreement to be satisfactory for holistic program assessment purposes.

Table I

Scoring Rubric for Unit Operations Laboratory Reports

Group members: ___________________________________ Lab Session: ______________ Experiment: ___________________

Objective	4 Exemplary	3 Proficient	2 Apprentice	1 Novice	Score
ChE graduates will be able to apply knowledge of unit operations to the identification, formulation, and solution of chemical engineering problems.	Student groups apply knowledge with virtually no conceptual or procedural errors affecting the quality of the experimental results.	Student groups apply knowledge with no significant conceptual errors and only minor procedural errors.	Student groups apply knowledge with occasional conceptual errors and only minor procedural errors.	Student groups make significant conceptual and/or procedural errors affecting the quality of the experimental results.	
ChE graduates will be able to design and conduct experiments of chemical engineering processes or systems and they will be able to analyze and interpret data from chemical engineering experiments.	Student groups design and conduct unit operations experiments with virtually no errors; analysis and interpretation of results exceed requirements of experiment and demonstrate significant higher-order thinking ability.	Student groups design and conduct experiment with virtually no errors; analysis and interpretation of results meet requirements of experiment and demonstrate some higher-order thinking ability.	Student groups design and conduct experiment with no significant errors; results are analyzed but not interpreted; very limited evidence of higher-order thinking ability.	Student groups design and conduct experiments with major conceptual and/or procedural errors; no evidence of significant analysis and interpretation of results; fail to meet requirements of the experiment; demonstrate only lower-level thinking ability.	
ChE graduates will demonstrate an ability to communicate effectively in writing.	Written report is virtually error-free, presents results and analysis logically, is well organized and easy to read, contains high quality graphics, and articulates interpretation of results beyond requirements of the experiment.	Written report presents results and analysis logically, is well organized and easy to read, contains high quality graphics, contains few minor grammatical and rhetorical errors, and articulates interpretation of results which meets requirements of the experiment.	Written report is generally well written but contains some grammatical, rhetorical and/or organizational errors; analysis of results is mentioned but not fully developed.	Written report does not present results clearly, is poorly organized, and/or contains major grammatical and rhetorical errors; fails to articulate analysis of results meeting requirements of the experiment.	

Table II

Summary of Inter-rater Reliability Results Using the Scoring Rubric

Report	ChE students will be able to apply knowledge of unit operations to the identification, formulation, and solution of unit operations problems.	ChE students will be able to design and construct experiments of chemical engineering processes or systems and they will be able to analyze and interpret data from chemical engineering experiments.	ChE students will demonstrate an ability to communicate effectively in writing.
a	4,3,3,3	4,2,4,3	3,2,3,3
b	3,2,3,3	3,2,3,3	2,1,2,2
c	1,2,2,3	2,2,2,2	2,2,2,2
d	2,2,2,3	2,2,2,3	2,1,2,2

Once inter-rater reliability was established among assessment committee members, we began the task of assessing a sample of reports from each of two 1998 summer laboratory sessions. Results are summarized in Table III. All reports produced by the students in the last two weeks of the course (approximately 65 per summer) were retained and a random sample of 20 was collected for assessment purposes. Each report was then independently assessed by two assessment committee members using the scoring rubric. As the results in Table III show, scores for 18 of the 20 reports agreed within 1 point for each objective (our reliability criterion) and therefore only 2 of the 20 reports had to be scored by a third faculty member. Such a high rate of agreement among a widely disparate group of faculty (two senior professors, one associate
professor, and one new assistant professor who has never taught the laboratory course) is not uncommon when the rubric development process recommended by Greene [8] is closely followed.

Table III

Results of Summer Lab Report Assessment (1998 Summer Lab Sessions)

Report	ChE students will be able to apply knowledge of unit operations to the identification, formulation, and solution of unit operations problems.	ChE students will be able to design and construct experiments of chemical engineering processes or systems and they will be able to analyze and interpret data from chemical engineering experiments.	ChE students will demonstrate an ability to communicate effectively in writing.
1	3,3	2,2	2,2
2	3,2	2,2	1,2
3	1,2	2,2	3,2
4	2,2	2,2	2,2
5	1,1	2,1	1,2
6	2,3	2,2	2,2
7	3,3	3,3	3,2
8	3,3	2,3	3,3
9	2,3	2,2	3,2
10	2,3	2,3	2,3
11	4,4	3,4	3,2
12	3,4,3	2,4,2	2,3,2
13	3,3	2,3	2,3
14	3,3	3,2	3,3
15	1,1	2,2	1,2
16	2,1	2,2	2,2
17	3,3	3,3	2,3
18	3,3	3,3	3,2
19	4,3	4,3	3,2
20	3,2,2	4,2,3	3,2,2
% of scores at 2 or above	80.0%	95.0%	85.0%
% of scores at 3 or above	50.0%	30.0%	10.0%
average score	2.6	2.5	2.3

Note: Each report was independently blind-scored by two CR assessment committee faculty members. Any scores which varied by more than 1 point in any of the three objective categories was scored by a third faculty member.

Scoring levels: Exemplary = 4, Proficient = 3, Apprentice = 2, Novice = 1

Once we obtained assessment data on the lab reports, we began evaluating the results and how we could use them to improve the unit operations laboratory course and our overall curriculum. As part of our assessment plan development, department faculty had agreed upon a stringent performance criterion for each of the three objectives being assessed: "100% of the reports will rate at 2 or above and 50% will rate at 3 or above." As shown in Table III, we are not yet meeting our performance criterion for any of the three objectives, although students are performing reasonably well in all three areas. These data are now being used to guide faculty discussions about what specific curricular changes are needed to further improve student performance. Possibilities under consideration include adding new unit operations learning objectives to pre-requisite courses in fluid mechanics, heat transfer, and mass transfer; more emphasis on data analysis in chemistry and physics laboratory courses, and additional writing assignments in chemical engineering courses leading to the unit operations laboratory.

Conclusions and Recommendations

The unit operations laboratory course represents an ideal context for performance assessment of chemical engineering students. To obtain reliable and valid data requires a multi-step process to create and test scoring rubrics which clearly articulate the objectives being assessed and describe in detail each level of observed student performance. The process of developing a performance assessment plan is itself valuable because faculty members (for perhaps the first time) must discuss and agree upon the attributes of acceptable student work.

We have developed and tested an easy-to-use scoring rubric for using unit operations laboratory reports to assess three objectives: 1) knowledge of unit operations, 2) designing and conducting experiments and analyzing and interpreting data, and 3) written communication. Data from 1998 summer laboratory sessions indicate that the rubric is a reliable and valid means of holistically assessing student performance.

Based on our success assessing written reports, we hope to expand assessment activities in the laboratory to include performance in the prelab oral examination, oral presentations, and teamwork. We also plan to extend this method of assessment to other courses in the curriculum which contain project and laboratory work.

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