Three Approaches To Outcomes Assessment: Questionnaires, Protocols, and Empirical Modeling[a]

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Engineering is a multi-dimensional discipline. Practicing engineers must possess a variety of knowledge and skills to be successful in the workplace. Now, ABET, through "EAC 2000" has classified these into eleven categories[1]. ABET's new performance-based criteria require each engineering program's faculty to clearly enunciate educational objectives in terms of a diverse set of knowledge and skills. Further, the faculty must demonstrate that the program's graduates are, in fact, acquiring these knowledge and skills, and, where deficiencies exist, they are being corrected. This is a substantial challenge, which requires a comprehensive evaluation system. Clearly, an effective engineering education evaluation program must be multi-faceted, employing an array of methodologies which measure a variety of outcomes, and provide the requisite feedback for making programmatic improvements. We discuss three approaches to outcomes assessment that we are developing and testing. We then describe how these assessment approaches can be integrated into a formal evaluation program. These methods involve questionnaires about attitudes (freshmen and alumni), verbal protocol analysis, and empirical modeling. Each method has different objectives, and therefore serves a different purpose in a well-rounded evaluation program. The advantages and disadvantages of each method, as well as their integration are discussed.

Introduction

We are addressing the crucial problem of demonstrating that engineering students have received a quality education. What is a quality education? The American Society for Engineering Education's (ASEE) blue ribbon report, *Engineering Education for A Changing World*[2], proclaimed that "engineering education programs must not only teach the fundamentals of engineering theory, experimentation, and practice but be relevant, attractive and connected," preparing students for a broad range of careers as well as for lifelong learning. The National Science Foundation's complementary report, *Restructuring Engineering Education: A Focus on Change*[3] has a similar theme: Engineering curricula should be broad and flexible, preparing students for both leadership and specialist roles in a variety of career areas. The National Research Council's Board of Engineering Education[4] has also recommended a number of actions for curriculum reform "including early exposure to 'real' engineering and more extensive exposure to interdisciplinary, hands-on, industrial practice aspects, teamwork, systems thinking and creative design." The ASEE report argues that because "engineers now operate in a world where their accomplishments are often more limited by societal considerations than by technical capabilities, they are engaging in a wider range of activities throughout their professional lives." Hence, today's education must prepare students for this changing workplace, providing the "technical knowledge

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and capabilities, flexibility and an understanding of the societal context of engineering." To the ASEE, "coursework should feature multidisciplinary, collaborative, active learning and take into account students' varied learning styles."

All these concerns are captured in the "EAC 2000," the recently released criteria for accrediting engineering education programs, which specifies that "Engineering programs must demonstrate that their graduates have:

- An ability to apply knowledge of mathematics, science, and engineering;
- An ability to design and conduct experiments, as well as to analyze and interpret data;
- An ability to design a system, component, or process to meet desired needs;
- An ability to function on multi-disciplinary teams;
- An ability to identify, formulate, and solve engineering problems;
- An understanding of professional and ethical responsibility;
- An ability to communicate effectively;
- The broad education necessary to understand the impact of engineering solutions in a global/societal context;
- A recognition of the need for and an ability to engage in life-long learning;
- A knowledge of contemporary issues; and,
- An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.[5]"

As Rogers notes, EAC 2000 has changed the focus from "what are you [the program] doing" to "how is what you're doing achieving the desired outcomes [what are your students doing][6]" That is, accreditation now will be concerned with outcomes rather than input or process. A major requirement is the implementation of an effective evaluation system which enables outcomes to be measured, interpreted, and the results fed back to the faculty in order to improve the educational process. Such systems do not currently exist. Consequently, EAC 2000 is causing the engineering education community to now create methodologies for on-going program assessment and evaluation; methodologies which are sensitive to each program's objectives. As a first consequence of EAC 2000, the Joint Task Force on Engineering Education Assessment issued a "*White Paper*[7]" which calls for the development of multiple assessment tools to assist in the evaluation of engineering program quality. Here we present three methodologies applied originally at the University of Pittsburgh and now being adapted at the University of Texas - El Paso. These are:

- Attitudes and outcomes assessment based on freshman and alumni questionnaires,
- Evaluation of student design processes using verbal protocols, and
- Empirical modeling techniques that provide the much needed relationships between "what students are doing" and "what the program is doing."

When combined together, these methodologies will provide a comprehensive evaluation system with sufficient flexibility to satisfy the needs of a wide spectrum of engineering programs.

Attitudes And Outcomes Assessment Using Questionnaires

Assessment using well designed and tested questionnaires can provide valuable feedback for evaluation and continuous improvement. We have used questionnaires to measure:

- Freshman perceptions about themselves and their abilities to succeed in engineering, and
- Engineering alumni reflections about their experiences while attending school and their competencies at time of graduation.

These questionnaires have been used to assess several aspects of our engineering programs and are described below.

Freshman Attitudinal Assessment

The Pittsburgh Freshman Engineering Survey© is used to assess engineering students at both the beginning and the end of the freshman year. (See [8,9,10] for complete descriptions.) Originally developed as part of comprehensive evaluation of new curricula, it provided a comparison of pre- and post- changes in attitudes, particularly in relation to retention initiatives. Consequently, the instrument serves two important purposes in a comprehensive evaluation system.

First, the information obtained with this instrument provides a means of assessing the attitudes which different freshmen bring to their engineering studies. This insight into the characteristics of our freshman classes establishes a valuable baseline, and better informs us as to which freshmen educational objectives may require additional stress. For example, over the past four years we have observed a significant positive trend in the attitudes of our entering freshmen relative to their initial impressions of engineering. (See Table 1.) This suggests that initiatives to better inform prospective students about engineering have been effective, and these students may be more inclined to remain in engineering. (We have documented that freshmen who left engineering in good academic standing, began the year less committed to engineering than those who stayed[11].)

Year	Male	Female
1994	3.82	3.67
1995	3.86	3.81
1996	4.29	4.29
1997	4.28	4.32

Table 1. Positive Impressions of Engineering -
Entering Freshmen Engineering Students at the University of Pittsburgh (Scale 1 to 5)

Second, knowledge of changes in attitude over the first year provide insights into how a particular program impacts its students. Consequently, this provides another important program evaluation tool. For example, in a study jointly conducted with Porter, Felder, and Fuller at North Carolina State University[12,13], we are using the survey instrument and accompanying measures to learn how differences among three curricula and pedagogical approaches to freshman engineering programs contribute to attitudinal changes[14]. Of particular interest are those students involved in NC State's Integrated Mathematics, Physics, Engineering and Chemistry curriculum (IMPEC). We have already observed important year-end changes in attitude even though the three groups were not substantially different at the beginning of the freshman year. (See Table 2.)

The NC State traditional group exhibited significant changes in the negative direction of several attitude measures indicating that students' expectations about engineering and their education may not have been met during the first year. Such results are comparable to those previously obtained at Pittsburgh prior to the introduction of a peer mentoring program (specifically designed to counter these negative changes)[15,16]. In contrast, the IMPEC students exhibited no decreases in attitudes for these measures. In addition, positive trends with respect to confidence in chemistry, and basic engineering knowledge and skills were exhibited by the IMPEC group, clearly objectives of that innovative program. This implies that IMPEC was effective in maintaining student expectations, as well as improving students' attitudes and confidence. In addition to exhibiting declines comparable to the traditional NC State students, Pittsburgh students also indicated a perceived decrease in their engineering abilities over the course of the freshman year. However, these same students' perception of engineering compared to other fields increased favorably as did their enjoyment of working in groups. These were two specific objective of the Pittsburgh Freshman Engineering Program. These results support using the instrument as a program evaluation mechanism.

Student Attitude and Self-Assessment Measures	**NC State Traditional**	**NC State IMPEC**	**Pittsburgh**
General Impressions of Engineering	↘	—	↘
Financial Influences for Studying Engineering	—	—	⇡
Perception of the Work Engineers Do and the Engineering Profession	↘	—	↘
Enjoyment of Math and Science Courses	↘	—	↘
Engineering Perceived as Being a "Precise" Science	⇣	⇣	↘
Engineering Comparing Positively to Other Fields of Study	—	—	↗
Family Influences to Studying Engineering	↗	—	⇡
Confidence in Chemistry	↘	⇡	—
Confidence in Communication Skills	—	—	—
Confidence in Basic Engineering Knowledge and Skills	—	⇡	⇡
Adequate Study Habits	↘	—	—
Working in Groups	—	—	↗
Engineering Abilities	—	—	↘
Key: ↘ significant change ⇣ trend — no change			

Table 2. Attitudinal Changes Over the Freshman Year

Alumni Questionnaire:

As noted above, a major objective is to develop outcome based models of educational programs. A well-designed survey of alumni can provide much of the necessary data to construct such models. As a first step, we have developed, evaluated, and validated a prototype model for an Industrial Engineering program[17], and are proceeding to extend this to five other programs. When fully developed and implemented, this type of model should provide a much needed feedback mechanism to make improvements to the engineering educational system processes.

We propose that the outcomes of an engineering education are the knowledge, skills, and attitudes that the new graduate possesses. These outcomes are affected by a number of educational processes (e.g., curriculum, in-class instruction, work experiences, etc.) which the individual experiences as he/she matriculates towards graduation. Figure 1 presents these processes and outcomes as part of a conceptual model of the engineering education system. Here processes have been split into two categories: those hypothesized to be core or primary to obtaining an engineering education, and those hypothesized to either enable an individual to attend college and/or enhance their engineering education experience (i.e., enabler/enhancer).

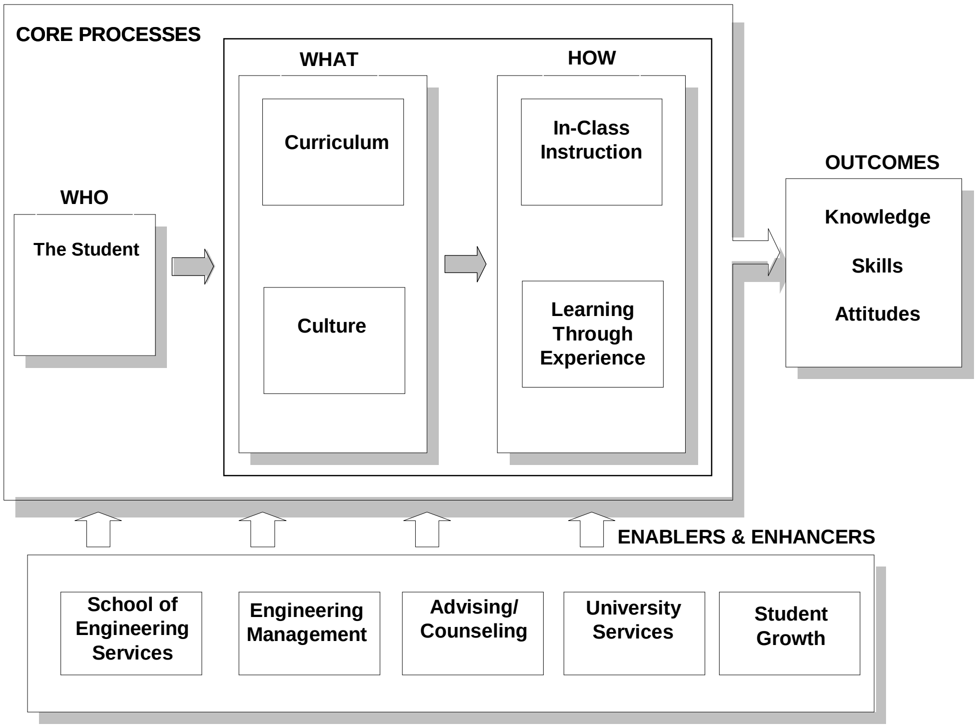

Figure 1. Conceptual Model of the Engineering Education System

Using the Department of Industrial Engineering at the University of Pittsburgh, a pilot model was evaluated and validated. Again, a questionnaire was developed to obtain data about the outcomes of an engineering education, as well as capture information about the processes the graduate experienced while obtaining his/her engineering degree. The set of outcome measures representing the knowledge, skills, and attitudes an individual should possess at graduation was derived by focus groups of practicing industrial engineers from the Pittsburgh area. The resultant 15 outcomes were markedly similar to those proposed by the ABET. (See [18] for specific details.) The attitude assessment instrument was distributed to roughly 900 industrial engineering alumni from the University of Pittsburgh (graduating between 1970 and 1995). A one-third response rate was obtained providing sufficient data to both empirically build and validate the model.

A factor analysis conducted on the questionnaire responses found that alumni differ in how they viewed the processes of their engineering education. Primary differences were observed in two of the processes: perceptions of the “curriculum” and “in-class instruction.” Specifically, those engineers with pre-graduation work experience (i.e., co-op, internship or undergraduate research) perceived statements about curriculum and in-class instruction as one process, whereas engineers without such pre-graduation experience saw these as two separate entities. In addition, alumni with pre-graduation work experience rated aspects of the system processes, as well as their competencies at graduation, higher than alumni without pre-graduation experience. These results reinforce the value of providing such pre-graduation professional experience, and allow us to identify specific process areas for improvement, particularly for those students who ordinarily would not receive this experience.

Verbal Protocol Analysis For Documenting Engineering Educational Processes

A goal of many of curriculum innovations has been to improve students’ engineering design abilities. Yet, documentation of the success of such innovations has been allusive. One promising tool for documenting student design processes is verbal protocol analysis. Ericsson and Simon[19] have demonstrated the validity of the verbal protocol method and argue that it is a valid method to obtain data about thinking processes. To date, it has primarily been used as a research method in which individuals solve problems or perform a task while thinking aloud. By capturing the subjects’ thought processes on audio and/or video tape, transcribing the text and then coding it, a rich data set is obtained. Comparison of verbal protocol data can be used to evaluate differences between groups of subjects, or between a student group and a prescriptive model. Hence, it provides a complementary program evaluation method in which groups of students can be tested and compared to a control or comparison group in order to determine how specific classroom experiences have affected student learning.

As a start, verbal protocol analysis has been used to document the process engineering students use when they solve design problems. In one study, it was found that the process students use to solve short open-ended design problems improve after just one semester in engineering, both in terms of the time spent on the problem and the number of transitions between design process steps[20]. Verbal protocol analysis has also been used to assess the effects of new curricula and courses on student learning. Some researchers have done experiments that used verbal protocols to compare students that complete traditional courses with those that have taken more innovative courses. For example, Rogers and Sando[21] video-taped matched groups of students solving a design problem. One set of student groups had been through an experimental curriculum while the comparison groups had taken a traditional engineering curriculum. Preliminary results showed little differences between the groups.

We have used this technique extensively in our "playground studies," where students were asked to give a verbal protocol as they approached a playground design problem[22]. (This is a revised version of a term-long design project used at the University of Maryland as part of the National Science Foundation's ECSEL coalition)[23]. Students were asked to address this relatively unstructured problem, and were encouraged to ask the monitor for specific information or clarifications during the experiment.

Early results of the playground design experiment (based on 50 subjects) show that engineering students have a wide variety of approaches when problem solving. However, one consistent finding is that most student subjects, both freshman and seniors, do little information gathering. Although seniors asked for significantly more categories of information than freshmen, in general students' requests for information do not encompass the broad range of information that was available. Rather, students primarily concentrated on requesting information associated with material costs[24,25]. Further, these students did not cover the wide range of information that a comparison group of parents believed to be important. As a whole, students were not consciously aware of the need to gather accurate information about such issues as safety, demographics, and descriptive information about the local area.

As noted, seniors did somewhat better than freshmen. More than half of the seniors addressed issues such as material costs, safety, labor availability and costs, material specifications, and body dimensions. However, the seniors did not adequately cover other important categories including: information about the area, neighborhood opinions, utilities, neighborhood demographics, maintenance concerns, legal liability, and supervision. All of these are important aspects to consider when designing a playground.

Of particular relevance to evaluation is the comparison of the combined number of explicit requests and assumptions made by the senior students by discipline. Civil Engineering students (CEs) averaged a total of 12.7 requests. In contrast, Industrial Engineering students (IEs) averaged 36.8 total requests, and the Mechanical Engineering students (MEs) averaged 30.7 total requests. Of these requests, CEs averaged a total of 4.8 different information categories, while the IEs covered 9.4 categories, and the MEs covered 7.1 total categories. Using Tukey's T method and a 95% confidence level, we found that CEs differed significantly from IEs on total requests and total categories. The difference between CEs and MEs was significant only on the total number of requests. There were no significant differences between IEs and MEs; however, with larger sample sizes, significance might be observed.

These initial results demonstrate the potential use of verbal protocol analysis for evaluating student learning. Our preliminary data suggests that the Civil Engineering faculty should reexamine their curriculum and consider introducing units and course material aimed at improving those areas where performance was low. Once such changes have been introduced, the verbal protocol analysis should be repeated. By continuing to obtain verbal protocols of individuals as well as groups of students solving design problems, we will build an important evaluation data base.

While the type of verbal protocol analysis described here is a time consuming research method, several ways have been suggested to shorten the effort, but still gain comparable insight. For example, protocols of students solving problems do not have to be transcribed in their entirety. Rather, the data can be used to create a script that identifies specific aspects of the problem solving approach. This is particularly useful for students solving problems in teams; e.g., rather than transcribing a conversation word for word, one can simply record who was talking to whom, about what and when[26]. Instructors can also gain valuable insight into student problem solving approaches by listening to audio tapes or watching videotapes of students solving problems. Leifer, et. al.[27,28,29] describes a research method known as video-based interaction analysis for studying human activity. This qualitative method has been used in the classroom to study student design processes.

Identifying Relationships And Establishing Feedback Mechanisms: Use Of Empirical Modeling

The freshman and alumni questionnaires have given us much useful information about the various educational processes an individual experiences while attending school and through reflection of the past. Verbal protocols have allowed us to obtain more insight about the thinking processes a student experiences during the design process. Next, through the use of empirical modeling techniques, we are investigating relationships between these processes and their resulting outcomes. Understanding the nature of these relationships allows us to fully evaluate the program by providing the correct feedback for continuous improvement. Specifically, we are looking at relationships between:

- The initial attitudes freshmen have and retention in the engineering program,
- The educational processes an individual experiences while obtaining an engineering degree and the expected outcomes at graduation, and
- The design process a student follows and the quality of the final design or product.

Using logistic regression models, we established a relationship between the attitudes incoming students have about themselves and their ability to succeed in engineering and whether or not they may leave engineering during their freshman year in good standing (GPA $\geq$ 2.0). The attitude measures found to be primary in predicting attrition were: *whether or not an individual liked engineering, confidence in basic engineering background knowledge, and enjoyment of math and science courses*[30]. This model has been used by freshman advisors to identify students who may potentially leave the program, so that the needs of these individuals may be addressed properly.

We have also used multiple regression to determine whether relationships exist between the educational processes an individual experiences while obtaining an engineering degree and the fifteen outcomes of an engineering education as measured by alumni feedback. Two sets of models were developed: one set for engineers with pre-graduation experience and the other set for engineers without pre-graduation experience. For many of the predicted product outcome measures, as much as forty to sixty percent of the variation could be explained for by the process variables in the model. It would appear that these relationships are not very strong. However, given a system and student population with large inherent variation, a number of the relationships were, in fact, substantial. In particular, for alumni that had pre-graduation engineering experience, creditable regressions were developed for the following outcome measures: *IE specific knowledge, problem solving abilities*, *creative thinking*, *teamwork skills*, and *professional traits*. For alumni without experience, good regression models were developed for: *knowledge of latest technologies, problem solving abilities*, and *engineering ethics*. Further, these regressions indicated that the core processes had more of an impact on predicting the respective outcome measures than the enabler/enhancer processes, thus confirming our initial assumptions. Knowledge of these relationships allows us to target those specific processes that will have the greatest impact on improving the outcome measures. For those outcome measures that did not yield notable relationships, it is possible that these are influenced by variables outside the model system, as defined in Figure 1.

Finally, we have assume that by utilizing an active, iterative design process, the student's potential of achieving a high quality design or product increases. However, we do not know the extent that this relationship actually exists and what aspects of the design process relate best to the quality of the product. Currently, we are looking for those relationships between the playground design process protocols and the final designs. To judge the quality of the subject's final design, we have developed a quality score. This score is based on three parts: (1) criteria based on the problem statement, (2) applicable supplemental criteria, and (3) qualitative ratings (aesthetics, design uniqueness, technical feasibility, etc.). Final design scores are linked to the quantitative data produced from the coded verbal protocols. When completed, these models will provide valuable insight about those design processes that contribute most to the quality of the final design, as well as indicate areas where teaching efforts may need to be concentrated[31].

Conclusions

We have described three methods which, when used together can provide a thorough evaluation system. They enable engineering educators to assess students when they enter, at the end of the freshman year, at a number of points in between, and as alumni reflecting on their educational experience. All three provide rich databases for model building and additional analysis. Verbal protocol analysis, in particular, is a powerful tool that can be used to understand aspects of the educational process, since it enables us to look at student learning in detail rather than simply "grading" a final solution. By measuring both the "product" and the "process," we can then explore whether a relationship exists between the type of process a student uses and the quality of the end result. Knowing this relationship, we can then distinguish between good and poor processes and indicate specific problems that may be addressed in our curricula.

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