Int. J. Engng Ed. Vol. 17, Nos. 4 and 5, pp. 479–482, 2001
Printed in Great Britain.
0949-149X/91 $3.00+0.00

Teaching Design by Integration throughout the Curriculum and Assessing the Curriculum using Design Projects*

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An excellent paradigm for design education is the integration of design throughout the undergraduate curriculum. The design skills desired of graduates are introduced in the first course and developed throughout the curriculum via projects each semester. These skills are reinforced continuously, and students receive constant feedback regarding their mastery of these skills. The traditional capstone course is used to polish these skills further rather than being the first and/or only place in the curriculum where these skills are taught. Any design project, particularly the capstone project, also provides an excellent assessment measure. After a design project presentation, the question and answer period can be a rich source of assessment information. Students get immediate feedback on their work, and faculty, through questions and follow-up questions, can determine in great detail the level of each student's understanding of and ability to apply fundamental principles. This paradigm also develops oral and written communication skills, provides students the opportunity to develop these skills with periodic feedback, and provides faculty with the opportunity to assess the development of these skills.

INTRODUCTION

IN THE TRADITIONAL curriculum, knowledge of the field is gained via a series of courses that are often taught as if they were unrelated. The faculty might understand the knowledge structure of the field, but the students do not yet have this insight. Students become proficient at solving well-defined problems at the end of chapters, and they know that they can find the subject matter for that problem somewhere in the chapter. Then, when students reach the fourth year, sometimes only in the final semester, they encounter a 'capstone' course in which they are expected to solve complex, open-ended problems that require synthesis of the knowledge gained in previous courses. They are expected to prepare written reports of their solutions and make oral presentations defending their solutions. In this 'capstone' experience, they often encounter, for the first time, economic considerations, in which the best global solution is not necessarily the best solution for each individual component of the problem. A superior paradigm for design education is integration of design throughout the undergraduate curriculum. We call this the holistic curriculum [1]. In the holistic curriculum, open-ended problems are assigned throughout the curriculum. A semester project covers application of the content of all courses taken simultaneously. Oral and written presentations are required each semester, and economic considerations are introduced in the first course. The skills desired of graduates are introduced in the first course and developed throughout the curriculum. These skills are reinforced continuously, and students receive feedback each semester regarding their mastery of these skills. The capstone course is used to polish these skills further and to attack more in-depth problems rather than being the first and/or only place in the curriculum where these skills are taught. For example, in our design class, we are able to include analysis of existing designs such as troubleshooting and debottlenecking in addition to design of new processes [2, 3]. In the following discussion, the term 'design problems' refers both to the design of new processes and the analysis of existing processes.

ENGINEERING DESIGN COMPONENT

The design component of the chemical engineering curriculum at West Virginia University has three parts. First, there is the use of a single design project for the second (sophomore) and third (junior) years. Second, there is the year-long, large-group project led by a student chief engineer in the fourth (senior) year. Finally, there are the individual design projects required in the fourth (senior) year. First year (freshmen) are not involved in this program because, at our university, first-year students are in a common program and have not yet declared their major.

* Accepted 27 November 2000.

Second and third years

A single chemical process is the basis for the design sequence during the second and third years. Each semester's design requires additional knowledge and more detail including mastery of the previous design. The first-semester, second-year student is introduced to a simple process flowsheet that typically includes a reactor, separator, and recycle stream. Cost data for feed and product streams are provided. Students are provided with alternatives, such as feed stocks and recycle rates, and are required to select the best operating conditions.

In the second semester of the second year, students are provided with a more complicated flowsheet that includes heat and work units. Utility costs are provided and are included in the evaluation. Students learn that heating, cooling, and power cost money. This affects the selection of operating conditions. As the students' understanding of the process is enhanced, the quality of their decisions improves.

In the first semester of the third year, thermodynamics, heat transfer, and fluid flow are covered. For the first time, students learn how to calculate the area of heat exchangers, evaluate the work/heat requirements for systems of staged compressors with intercoolers, determine the number of adiabatic (equilibrium) reactors in series, handle the non-ideal behavior of gas mixtures, and determine the size of process piping. All of these studies are needed for the new design. For the first time capital costs are considered in the analysis. The use of process simulation software is also introduced in this semester.

The design in the second semester of the third year differs in one major aspect. Students are not given a suggested flowsheet as a starting point. They are provided kinetic information that describe different reactor performances, and they are required to examine the separation units. With the experience developed from the previous designs and new information on separations and kinetics, a new improved process is synthesized.

As a result of these design projects, students develop personalized strategies for life-long learning. They:

- learn *self-evaluation;*
- experience *teamwork;*
- recognize the *role of economics* in decision making;
- appreciate the *need to understand basic principles;*
- understand the various *sources of engineering information.*

Since group written reports are required each semester and group oral reports are required for all but the first semester, students also learn the importance of:

- developing *communication skills.*

One of the principles of assessment as stated by the American Association of Higher Education is [4]:

> 'Assessment is most effective when it reveals an understanding of learning as multidimensional, integrated, and revealed in performance over time.'

By integrating design through the curriculum, students learn the practical applications of the material covered in class. They develop the ability to analyze complex processes, receiving reinforcement and feedback each semester. Oral and written communication skills are developed over time with feedback each semester. One result we have observed is the ability of our fourth-year students to organize an oral report and present it in a professional manner. Another result we have observed is the ability of our fourth-year students to attack more complex design problems than normally found in undergraduate chemical engineering curricula. We believe that another key end-result of integration of design through the curriculum is that our students achieve the highest levels of cognitive objectives in Bloom's Taxonomy: analysis, synthesis, and evaluation.

As an example of the advantages of the holistic curriculum, consider the role of economics in the design process. Prior to implementation of the holistic curriculum, our students usually did the economic analysis last. After all, since we only taught economics in the design class, it was one of the last things they learned in the curriculum! Now, by introducing rudimentary economics in the first class, they learn very early how the economic objective function drives decisions in the design process.

Our 'holistic' curriculum has all the typical engineering science components. The difference is that we teach engineering science within the context of practical applications. In the view of our faculty, there is a knowledge structure to the entire chemical engineering curriculum in which all topics among those generally accepted as belonging in the chemical engineering curriculum must be understood within the context of a chemical process in order to be considered learned. For example, in order to understand how a heat exchanger operates, it is necessary to understand the principle of resistances in series. However, in a real process, the operation of a heat exchanger is not solely governed by this one principle, but depends upon the interaction between the heat exchanger and other pieces of equipment in the chemical process. It is the focus on this latter relationship that separates the holistic curriculum from the traditional curriculum.

Year-long, large-group, fourth-year design

The second component of the vertical integration of design is a unique, two-semester, fourth-year design experience in which students learn to be responsible in a team environment and to work in an organizational structure. Under the direction of a student chief engineer, the class works for the entire academic year on a design project, beginning with a feasibility analysis and ending with a detailed, preliminary design. The project emphasizes team effort and teaches life-long learning skills.

Faculty play roles in the year-long design project. One faculty member is the 'client.' The client 'hires' the student company by communicating initially with their 'vice-president,' another faculty member. The group 'assigned' to the client is the fourth-year class, under the direction of the student chief engineer.

The goal of the fall semester of the design project is to do a feasibility study and to present alternatives to the client at the end of the semester. Before the beginning of the spring semester, the client makes a decision based upon the alternatives presented in the feasibility study. In the spring semester, the design is completed. The final product is a detailed preliminary design, as per the client's wishes, presented in a public forum.

The essence of the fourth-year design is that the students, not the faculty, are responsible for the project. The student chief engineer is free to organize the class in any manner. The usual result is one layer of management, with the class divided into groups of 4–6 students, with each group under the direction of a group leader. The chief engineer coordinates and distributes tasks among the groups, and the group leaders assign the group members' component parts of the task. The group leaders are responsible for ensuring that the task is completed, ensuring that all group members contribute as equally as possible, and reporting the results to the chief engineer and/or the client. Students evaluate group leaders and the chief engineer, group leaders evaluate the chief engineer, the chief engineer evaluates the group leaders, and the group leaders evaluate the students. Communication is important, between students and the client (described below) as well as among students. Internal memoranda allow all students to keep track of what has been done and avoid duplication of work.

If the students need help, they go to their vice-president, not the client. The client maintains a professional distance in the context of this project. Part of the role-playing for the client can be to act deliberately stupid or even unreasonable. Students learn to negotiate with the client. In fact, students participate in the initial definition of the project, and any change in its scope involves a negotiation between the students and the client.

It should be noted that, from our experience, 25–30 students appears to be a critical number of students. When class sizes exceed this number, we have found that the group is too large for one chief engineer to manage. For this situation, we have two different projects, two groups, two chief engineers, two clients, and two vice-presidents (still with two faculty members total, each assuming a different role in each project).

INDIVIDUAL DESIGN PROJECTS

Individual design projects are the third component of the design content of the curriculum, and are required in the fourth year. Any design project provides an excellent opportunity for assessment. The integrated design projects are more useful as feedback instruments for students to develop desired skills over time; although, an assessment can be made from the project regarding what students have learned in that semester. A capstone experience is one of the best opportunities for assessment of design skills, communication skills, and knowledge of the field. One key to using the capstone design experience for outcomes assessment is the measurement method. For over 25 years, fourth-year students in chemical engineering at West Virginia University have been required to do a series of projects in the two-semester, capstone design course, submit a written report, and defend their results to an audience of at least two faculty [5, 6]. A typical defense lasts one hour, with a 15–20 minute presentation followed by a question and answer session. Students do these projects and defend them individually. The question and answer period is tantamount to an individual tutorial. Students get immediate feedback on their work, and faculty can determine in great detail the level of each student's understanding of and ability to apply fundamental principles.

Oral examinations like this have advantages and disadvantages as an outcomes assessment measure [7]. The advantages include the ability to measure student learning in great detail through follow-up questions. Faculty can learn how and why students obtained their results and understand students' thought patterns. This makes it easier to determine if a reasonable result was obtained by accident from a series of unreasonable procedures. Additionally, the immediate student feedback is an excellent learning experience. Oral and written communication skills are also polished. The major disadvantages to this method are the faculty time required and the potential for this situation to intimidate students.

In addition to the direct impact on students, faculty are provided the necessary input to assess student performance in the application of engineering principles. The feedback provided by the fourth-year design projects affects the content of the second and third year design projects. This is one mechanism used to ensure that graduates meet minimum standards of knowledge and skills. This feedback measures learning directly and aids in curriculum development and improvement.

Assessment results from this exercise are used in several different ways, all of which 'close the loop' on the assessment process [8]. As already mentioned, the one-hour presentation and question and answer period provides students with immediate feedback on their work. After each presentation has been completed, class time is devoted to project review. One or two of the best student projects are presented. Faculty review the problem, emphasizing areas where better solutions could have been presented. Follow-up problems are usually assigned. An assessment report following each project is also prepared and circulated to all faculty. It describes the project, what types of solutions were expected, and what types of solutions were actually submitted. Areas where students did well are pointed out. Areas where a significant number of students were found to be deficient are also pointed out. In these cases, remedies to ensure that future students are not deficient in the same area are suggested.

SUGGESTIONS FOR IMPLEMENTATION

There are several possible ways in which existing design experiences can be adapted as assessment measures. A simple assessment plan can include evaluation of the final products of any capstone experience. A better assessment plan would be based on gathering information on how students use and apply previously learned knowledge and what alternatives are accepted and rejected and why. This is the information students are instructed to omit from the final report; it is the history of how the final result was obtained. There are several possible ways to gather this information. Students could be asked to keep a diary of what they did, alternatives they considered, and dead-ends they encountered. This diary would be submitted weekly or periodically during the semester and evaluated by the instructor from an assessment perspective (not for a grade). The purpose of keeping the diary may need to be explained to the students in order for them to take the assignment seriously. We have observed that the nature and scope of questions asked during a capstone experience can yield valuable assessment information. Therefore, a periodic, formalized question and answer session for each group should yield useful information on the level of student understanding and on their misconceptions. An interim presentation (or two) or periodic meetings with a mentor, in which the interaction were documented in detail, could yield the same information.

CONCLUSION

Vertical integration of design experiences through the curriculum is an excellent method for developing design, communication, teamwork, and self-evaluation skills. The development of these skills over time with the benefit of periodic feedback is a key assessment principle. Since all design experiences involve application of basic knowledge, they are a rich assessment opportunity, particularly capstone experiences. One of the best methods for obtaining assessment information from capstone experiences is via questioning students during an oral presentation of their results.

Acknowledgements—A program such as the one described here requires the cooperation of many faculty members. The following individuals have taught classes at West Virginia University in which the design projects described above have been used: Richard C. Bailie (emeritus), Eugene V. Cilento, Dady Dadyburjor, Hisashi O. Kono, Edwin L. Kugler, Aubrey L. Miller, Richard Turton, Wallace B. Whiting (currently at University of Nevada, Reno), John W. Zondlo.

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