R. S. Huss, M. F. Malone, M. F. Doherty, M. M. Alger and B. A. Watson, in *Fifth International Conference on Foundations of Computer-Aided Pprocess Design*, M. F. Malone, J. A. Trainham, B. Carnahan (Vol. Eds.) *AIChE Symposium Series*, no. 323, v. 96, American Institute of Chemical Engineers, NY, pp. 163-175 (2000).

DECISION-MAKING BY DESIGN: EXPERIENCE WITH COMPUTER-AIDED ACTIVE LEARNING

Michael F. Doherty, Michael F. Malone and Robert S. Huss
Department of Chemical Engineering
University of Massachusetts
Amherst, MA 01003-3110

Montgomery M. Alger and Brian A. Watson
GE Plastics
1 Plastics Avenue
Pittsfield MA 01210

Abstract

Advances in computer aided design and simulation tools and reduced computing costs allow new uses for computing in engineering education. Models of sufficient fidelity and speed allow solutions of realistic problems as an integral part of the course experience. This allows a new emphasis on the importance of making, justifying and evaluating decisions in process design. This paper describes our experience over several years and courses in implementing and testing this approach to design education. We find that use of simulation and design tools as an integral part of lectures has a major impact on student evaluations, if roughly 30% of class time is spent using these tools for active learning.

Keywords: Conceptual design, process synthesis, decision-making, education

Introduction and Motivation

In our view, the role of the engineer in industry is to make, evaluate, and justify decisions in support of business. There is a growing need in design education to provide students with the skills needed to make and justify engineering decisions in support of business in a competitive global marketplace. We are developing and implementing a comprehensive plan to address these concerns in a new undergraduate curriculum model that emphasizes interactive learning and realistic applications in process engineering throughout the course of study. The goal is to develop a curriculum, which provides students early and ongoing exposure to a framework for decision-making and understanding of the impact of decisions on economics, environment, safety and operability. There is an emphasis on invention of a better process across all curriculum areas. To implement change on this scale we use a new teaching infrastructure in a "classroom of the future" and strategies to insure ongoing and rapid integration of industrially relevant research and manufacturing trends in the classroom.

This rather old and compelling idea of "learning by doing" goes beyond the particular application to design education. However, methods and the associated tools for design and process engineering are most advanced thanks in large part to advances detailed in previous FOCPAD Conferences and similar related meetings, e.g., Mah and Seider (1981); Westerberg and Chien (1984); Siirola, Grossmann and Stephanopoulos (1990); Biegler and Doherty (1995).

The chemical process industries remain one of the strongest segments of the worldwide economy. This is due to the cost-effectiveness of well-designed chemical processes as well as to inventive chemistry. However, as we enter the next century, the industry faces major new challenges through increased global competition, greater regulatory pressures, and uncertain prices for energy, raw materials, and products. These competitive concerns increase focus on processes with subsystems that have tighter integration and coordination, on computing tools that communicate with each other, and on consideration of multiple design criteria including profitability, safety, operability, quality, and the environment.

Traditional chemical engineering curriculum models do not address most of these issues. For example, much of the typical engineering curriculum is focused on closed-end analysis problems where a system is well defined and sufficient information is given to completely solve a problem. For example, a flowsheet is often the starting point in a senior "capstone" course on design, which is then focused on computer simulation of the system. This focus is an excellent training in analysis, but does not necessarily develop the skills to treat open-ended problems. The unique and essential factor in solving such problems is the invention and ranking of alternatives, which in essence reduces to decision-making.

In the last two decades, many new ideas and tools have been developed to complement simulation with synthesis, e.g., Douglas (1988), Biegler, Grossmann and Westerberg (1997), Seider, Seader and Lewin (1999). Conceptual design combines synthesis and analysis and forces an examination of the decisions needed to invent a process. Systematic approaches articulate the economic objectives, trade-offs and constraints from operability and control, safety, the environment, and product quality. Any or all of these factors can be critical in selecting among the potentially profitable process alternatives.

We stress that the approach outlined here is not intended to replace analysis based on fundamental principles, which is typically well covered in the curriculum. It is the intent, however, to use analysis as one ingredient in exploring and comparing alternatives that maximize economic objectives and meet the constraints.

Thus, the program addresses the following primary needs:

1. The need for early and continued exposure to design and related decision making in the undergraduate curriculum.
2. The need for a process to integrate recent and relevant research ideas into the chemical engineering curriculum.
3. The need to educate students in synthesis as well as analysis and to develop the attitude and skills needed to make and justify engineering decisions based on economic objectives and realistic constraints.
4. The need to increase understanding and appreciation for the role of technology and technology decisions in a global context and in relation to markets, transportation, exchange rates, etc.

Specifically, this project addresses change in six of fourteen required "core" undergraduate courses as well as and introductory course for the freshman year. These are: Introduction to Chemical Engineering (freshman), Material Balances (sophomore), Staged Operations (junior), Process Design I and II (senior) and Process Control (senior). The approach was also used in a graduate course on Process Control. We focus primarily on the junior and senior courses in this paper.

Infrastructure

Computer design aids and new technologies afford the real opportunity to significantly alter the way in which chemical engineering is taught. Indeed, the chemical engineering curriculum of the twenty-first century can make major use of a "classroom of the future."

Construction and furnishing of such a classroom was completed in time for use for in spring 1997. A schematic of the classroom is shown in Figure 1. The facility contains 28 computer stations networked to two central servers that provide software tools and eventually access to real-time experiments in an adjacent undergraduate laboratory[1].

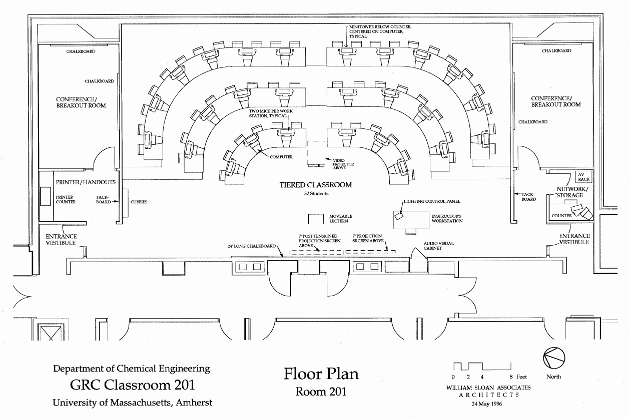

Figure 1. Schematic of the Classroom.

This enables hands-on, interactive use of the methods, tools, control algorithms and experiments. Each class is divided into pairs of two students per station that actively participate in the classroom and interact with the instructor and teaching assistants, in place of passive listening in traditional lecture formats. Video projection equipment provides real-time, interactive classroom display of results and experiments from any station in the facility.

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[1] We use 28 Pentium Pro 200's with CDROM and 4GB hard drives. This network is supported with a HP NetServer LH as the primary domain controller and a Dell Poweredge 4100 as the backup domain controller. All machines have Fast Ethernet cards to use the 100-mbps Ethernet network within the classroom. The network operates under Windows NT 4.0, with individual user accounts and security. General-purpose software (Microsoft Office 97, Netscape) was useful along with modeling and simulation software (Mathematica, MathCAD and Matlab). Specialist tools for chemical process design and simulation (HYCON and HYSYS) as well as computational chemistry and chemical education (Gaussian 94, Web Lab Viewer, Chemland, and several others).

This classroom is the basic, required, implementing tool, which is the foundation for the capacity to affect widespread curriculum change. It enables integral use of computer-aided design and analysis software such as Matlab, HYSYS, or HYCON for use in the courses. HYCON is a commercial package for designing nonideal distillation systems developed by Hyprotech Ltd. (now AEA software technology) based on ideas and a prototype developed in research at UMass. HYCON is one of the more specialized tools we use in the curriculum, but offers effective high fidelity models for complex mixtures. It is also an effective means to integrate selected research results with undergraduate teaching.

In fact, the particular choices of software always involve tradeoffs of fidelity and applicability to a particular subject vs. cost and ease of use. For instance, MathCAD is widely available and relatively inexpensive, but does not solve problems as effectively as Matlab in process control or HYCON in separations. New emerging standards for component software described elsewhere in this conference (Braunschweig et al. (1999)) offer the excellent potential for major advances in ease of use and impact. In fact, such standards and their use appear to be essential to long term success in this sort of approach to design education.

The cost of construction and furnishing the facility was approximately $425,000. If the facility is fully utilized, approximately 16 classes per year can be taught. For a lifetime of 3 years, the cost is just approximately $177 per student per course in classes of 50. In addition to the construction costs, operations bring the total to approximately $200 per student per course. The facility also serves as a computing lab in the evening hours, which is a further justification for the resources.

Industrial Advisory Board

An industrial outreach program fosters an ongoing dialogue with practicing engineers. This is accomplished through our existing research contacts in the UMass Process Design and Control Center. The most valuable input generally concerns the nature of the problem and the decisions encountered. Special emphasis was made on a balanced approach and intelligent use of the technology so that the students learn to make decisions, but also to keep a firm basis in the fundamentals and analysis. Input on sample problem definitions relating to business aspects of decision making is particularly helpful; one such problem is described below.

Curriculum Redevelopment

Although it was not envisioned at the outset, the effective use of technology for active learning permits and, in fact, requires a change in teaching approach. Traditional "stand-and-deliver" lectures and related assignments and exams (Fig. 2) are naturally replaced by tighter interactions between students and instructors (Fig. 3) and eventually teaching assistants (Fig. 4).

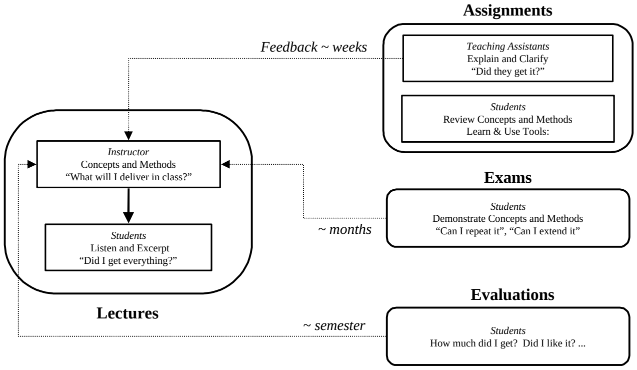


Figure 2. Staged Operations in 1995.

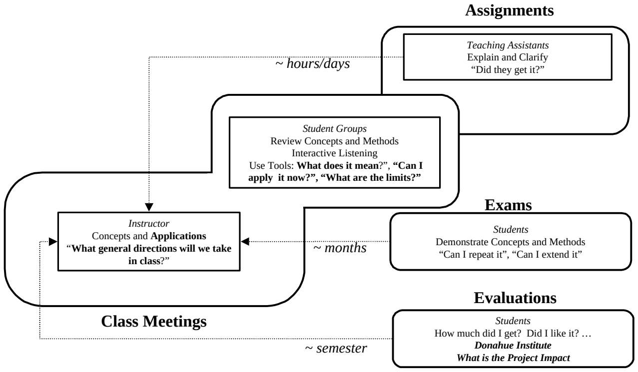


Figure 3. Staged Operation in 1998.

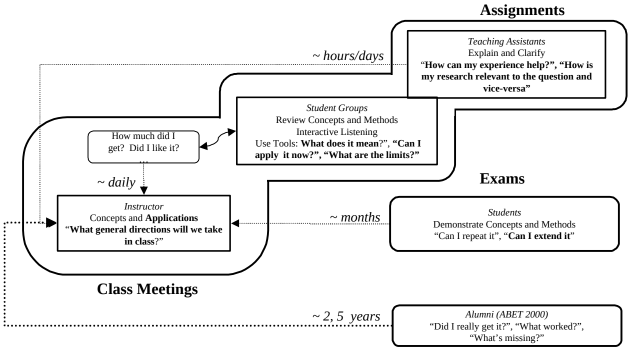


Figure 4. Staged Operations in 2000.

It is interesting that the classroom processes are becoming much more integrated in a search for improved educational impact, in close parallel to trends in chemical process design.

In what follows, we describe in detail our experiences and results for three courses, one each at the freshman, junior, and senior levels.

Freshman Introduction to Chemical Engineering

The objectives of this course were to provide design experiences in chemical engineering, to encourage teamwork, and to develop communication and computational skills for freshmen. This module gave an introduction to chemical engineering by way of designing and implementing automatic controller schemes to chemical processes. Computational skills were developed and utilized in the analysis of automatic controller schemes. Presentation and discussion of controller dynamics encouraged communication skills. The structure of the course required students to be divided into groups of three or four to encourage and develop teamwork during solution of simulation examples and experimental work.

The major lecture topics included

1. Overview of chemical engineering processes and the importance of automatic control in practice.
2. Dynamics of simple systems and differential equations.
3. Solutions of simple differential equations.
4. Computer-aided simulations of dynamic systems using MathCAD.
5. Effects of feedback on stability and performance.
6. Applications in chemical engineering, using computer simulations.
7. Classroom experiment using CIMCAR (see below)

Students solved control examples using computational and analytical approaches. These examples were tailored to chemical engineering by adapting cases from the senior level chemical engineering control course, simplified so that freshmen could solve them. A typical example was the design of a controller that sets a product yield requirement in a stirred tank reactor, which puts concepts from chemistry and mathematics courses into an engineering context for students. The solution of differential equations pertinent to control examples is probably the most difficult aspect for students to master in this course. To avoid the course evolving into a math course, the differential equations were handled mostly using computer software such as MathCAD, emphasizing graphical formulation and presentation of simulation results. Simulations of more challenging control applications in chemical engineering were performed in class using Matlab.

To provide hands on experience with an actual automatic controller, students conducted in-class experiments. Typical control examples in chemical engineering are not practical in the classroom. However, the types of dynamics encountered in chemical engineering are common to many examples in electrical and mechanical engineering. The classroom experiments involving an electric car (CIMCAR) already designed by Professor T. Djaferis in ECE was a useful vehicle for students to observe first hand the effect of controller schemes. Students used CIMCAR to test the effectiveness and related dynamics of different controllers during collision avoidance problems. Experimental results using an intelligent car (approximately 6 inches long equipped with a camera) were compared to the simulated performance predicted by theoretical models.

The course was highly interactive in nature, with an emphasis on active learning and presentations via group projects in class. Students were divided into groups of three or four when working on simulation examples and CIMCAR experiments. Group participation involved analyzing the behavior of the controller and presenting solutions graphically, orally and in written form. This aspect of the course allowed students to develop collaborative and communication skills that are vital in engineering.

Junior Year Staged Operations

The curriculum for this course differs significantly from the traditional approach to teaching separations. The focus is on the systems approach to separating nonideal, multicomponent mixtures of commercial complexity. The main new features are:

1. Inclusion of process economics. It is not typical to introduce this subject into separations courses. However, we believe it is vital to give students an appreciation of both capital and operating costs associated with separation processes so that the major tradeoffs can be taught and process alternatives can be screened effectively.
2. Emphasis on process alternatives. There is never a single way to solve an engineering problem, and this is true in separation systems as well as many other areas of engineering. We begin by making a precise problem statement (e.g., separate a ternary mixture of acetaldehyde, methanol and water of a given composition into pure streams with certain specifications on the allowable impurity levels) that allows for several alternative separation strategies. Students are required to rank the alternatives according to an engineering figure of merit such as the total annual cost, total energy use, etc. These concepts are reinforced by repeated application of the ideas on different systems. Once the students are comfortable with the idea of multiple solutions to a fixed problem statement they are introduced to...
3. Changing the problem statement to obtain a better solution. The problem statements that define process sub-systems (e.g., separation sub-systems) are often partial statements of the overall process system or the process goals. Better engineering solutions are frequently found by changing the sub-system definition or problem statement. For example, if two adjacent components are very difficult to separate it may be possible to eliminate one of them upstream before the

separation system, e.g., by reaction. In other cases, it may be necessary to redefine the problem statement to satisfy quality criteria, e.g., by over-purifying a stream beyond what is called for in the problem statement in order to eliminate undesirable impurities. Students were challenged with a number of "systems issues" of this kind and did a surprisingly good job at asking the right kinds of questions as well as answering them.

4. HYCON design tool. The HYCON design tool was an important aid in the solution of class problems. The new design methods taught in the lectures are too sophisticated for the students to program efficiently themselves. This tool allows them to get access to relevant data and procedures such as phase diagrams, residue curves, azeotrope bifurcation diagrams, etc. However, the program will not calculate anything that is not requested by the user, so it is impossible to get "cookbook" answers with no user input. The structure of the program requires that the user make decisions and know how to interpret the answers.
5. Making decisions. The major emphasis in the course is getting the students to make and justify decisions. Even in the early stages of the course, students were required to perform their own selection and specification of phase equilibrium and physical property models for realistic mixtures, including multiple components and realistic, nonideal physical properties. They quickly developed enough intuition to pick a suitable model and to justify their choice. Similar emphasis was given to the choice of complete process models (How and when do you include heat effects? How many components are included in the initial design? etc.). By the end of the course, most students were confident enough to solve difficult problems of industrial complexity with minimal input from the instructor.

Students quickly developed the intuition and confidence to pick a suitable physical property model and justify their choice. This was then extended to process models, problem definitions, and finally to the most important and open-ended task of problem redefinition. By the end of the course, many students were confident enough to define and solve difficult problems of industrial complexity.

The outcomes include:

1. Students were exposed to more realistic engineering situations.
2. Students learned to use a commercial-grade design tool at the cutting edge of new tools available.
3. Selected recent research results were implemented and taught to students much faster than has been traditionally possible. The lag time was cut by several years in this new environment.
4. Students were better at making and justifying decisions than their predecessors.
5. A significant amount of time was spent on interactive learning, but very little was removed from the course. This made the course longer, and an extra 30-40 minute class was taught each week, but the need for this has diminished in subsequent course offerings.

Senior Process Design II

M. F. Malone and A. Nagurney (Department of Finance and Operations Management) taught this course in the spring, 1997 semester to 38 seniors. Dr. Peter D. Edwards from the DuPont Company also participated through visits with classroom lecturing and discussion groups focused on financial evaluation of chemical processes.

This is the second in a two-semester sequence of courses in chemical process design. The main goal is to complete a systematic approach to understanding chemical processes begun in the fall semester. The fall semester Process Design I course is focused on continuous systems involving vapor-liquid mixtures and single plants. In the spring, these ideas are used as a basis for understanding interconnected manufacturing facilities, including processes to produce polymers and other solids. This naturally brings out the need to understand the interactions of process design and control.

Approximately 1/3 of the course was spent becoming familiar with some modern optimization tools, their use in assessing the economic impact of engineering decisions and how this information is used in a business context. Towards this end, part of the course provided a survey of the fundamentals of quantitative techniques to improve decision-making and management performance. Emphasis is on the formulation of decision problems as mathematical models and on the selection of the appropriate techniques for analysis and solution. This component of the course used Excel, along with specialized add-on solvers, to compute solutions to the models. Many actual successful management science model implementations by well-known companies were used as illustrations of the methods. Typical cases included oil blending and process design to warehouse location and distribution as well as portfolio optimization problems. Hence, applications were drawn from all functional areas of business including finance, marketing, and operations. The management science tools that were covered included linear programming; network models and some algorithms including the transportation problem and variants; the assignment problem; project planning networks; integer programming models; nonlinear programming applications; and the basics of formal decision theory.

Example 1: The DeRosier Problem

This in-class exercise is introduced during the nonideal and azeotropic distillation module of our junior year Separations course. The first part of the exercise is designed to be a mechanical application of the principles taught in class on the analysis and design of ternary azeotropic distillations. The second part challenges the students to find a creative design to a typical engineering problem that, on face value, is impossible to achieve. Most students can't do this, but the entire class benefits from the discussion that erupts during the attempt. This problem is named after Robert Derosier who was the first student to develop a successful design.

The problem statement is as follows:

> Part 1:
>
> Calculate the residue curve map for the mixture methanol-isopropanol-water at 1 atm pressure. Use the NRTL-ideal model to represent the VLE.
>
> Design a distillation column to separate a saturated liquid feed consisting of 40 mol% methanol, 40 mol% water, and 20 mol% isopropanol into saturated liquid products. The distillate is specified to contain 99 mol% methanol and 0.5 mol% water. The bottom product contains 0.5 mol% methanol. Use your engineering judgement to select a reflux ratio that trades off the vapor rate against the number of theoretical stages.
>
> Part 2
>
> After solving Part 1 you proudly show your design to the client who commissioned the job. She tells you that she wants as little water as possible in the methanol product because it kills the catalyst in her process. She will not accept methanol containing more than 50 ppm water. Since water is the heaviest component, this seems like an easy constraint to meet. Is it? What is the smallest composition of water that *you* can get in the methanol product? What is your design for the separation scheme?

The solution to Part 1 is straightforward and most students solve it rapidly. In Figure 5 we show the calculated residue curve map. Figure 6 shows the column composition profiles at minimum reflux, which is determined by the presence of a node pinch in the stripping profile just below the feed stage. We find $r_{min} = 5.0$. As a first estimate, we let the operating reflux ratio be 50% larger than the minimum value, and obtain the design shown in Fig. 7. The column has 28 theoretical stages with a feed on stage 6 (numbering from the top of the column).

Students typically begin solving Part 2 by successively lowering the mole fraction of water in the distillate and repeating the design strategy evolved for Part 1. Whereupon they find that when the distillate contains less than 3400 ppm water, the distillate composition lies in the lower distillation region and the rectifying profile does not intersect the stripping profile at any reflux ratio! This is shown in Figures 8 and 9. At this point many students feel smug that their superior engineering know-how has proved that the client cannot get what she wants. But in fact, she can, and the question is, how?

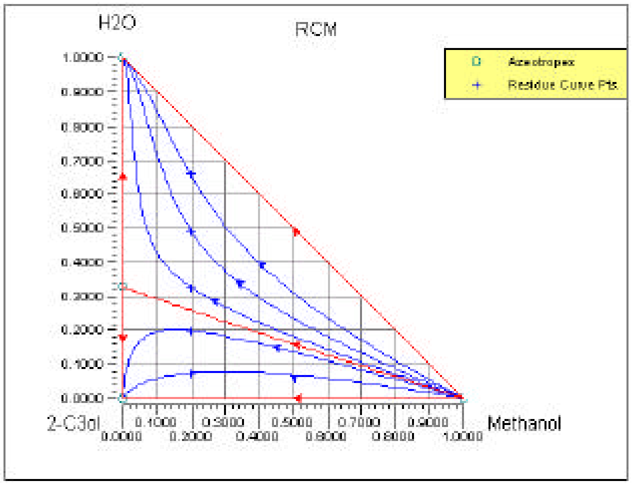
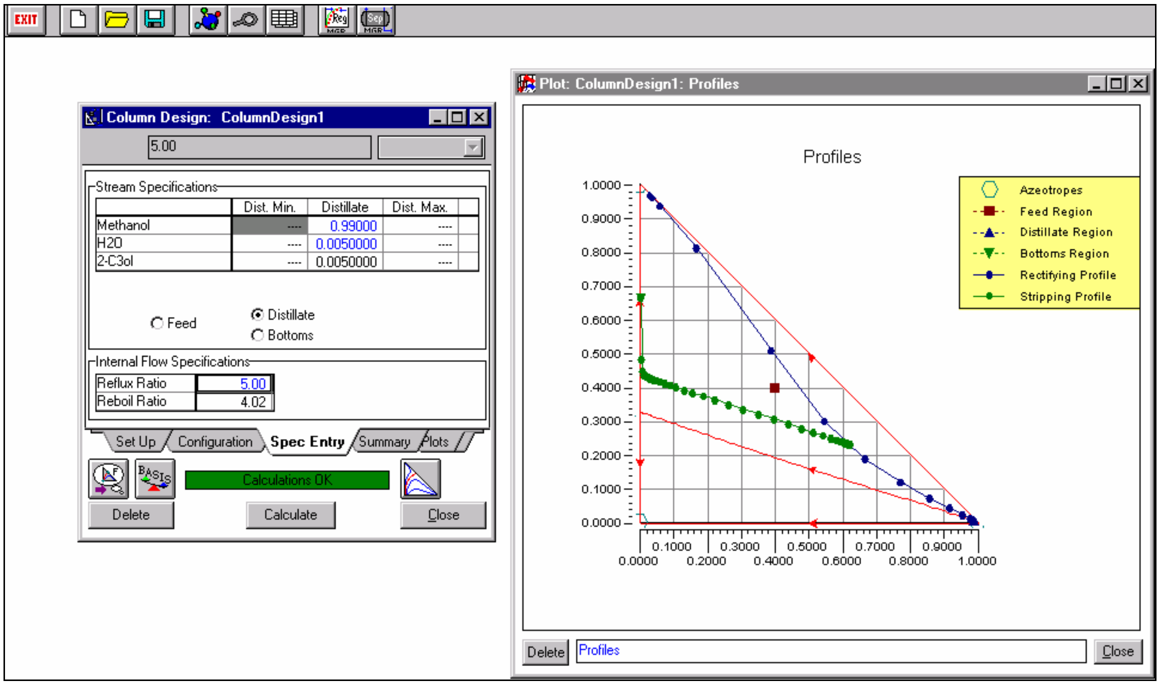


Figure 5. Residue curve map for the mixture methanol-water-isopropanol at 1 atm pressure.



5.00

Stream Specifications

	Dist. Min.	Distillate	Dist. Max.
Methanol	----	0.99000	----
H2O	----	0.0050000	----
2-C3ol	----	0.0050000	----

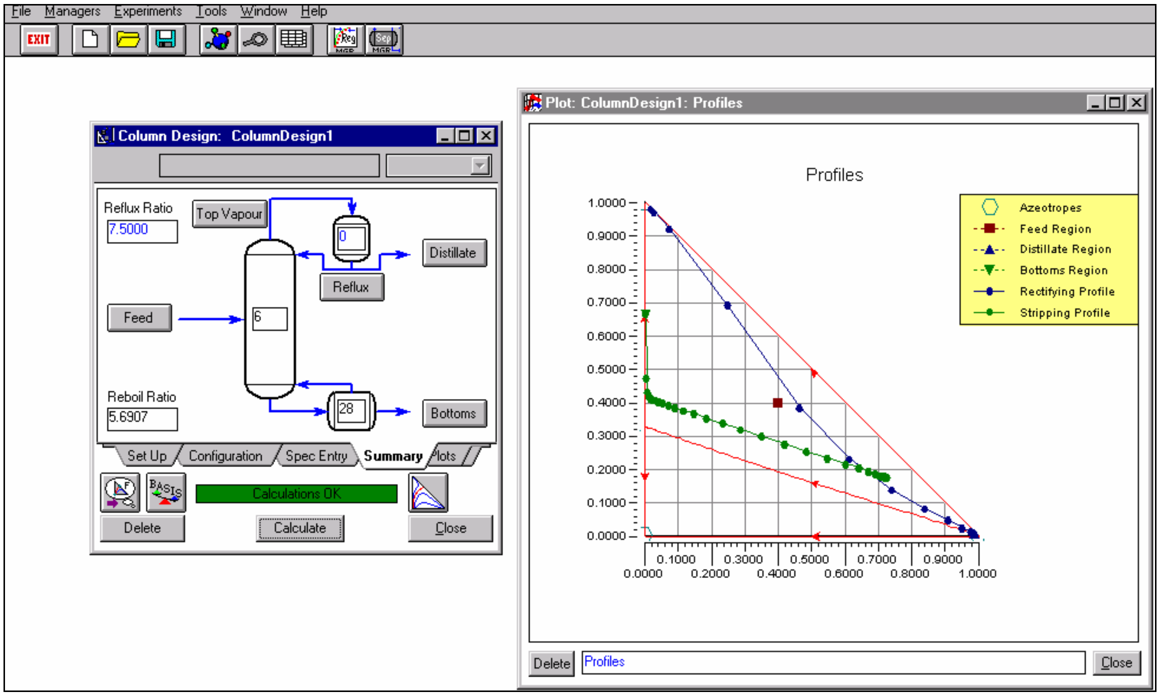
○ Feed
● Distillate
○ Bottoms

Internal Flow Specifications

Reflux Ratio	5.00
Reboil Ratio	4.02

Profiles

Figure 6. Minimum reflux profiles, r_{min}=5.0.



Reflux Ratio
7.5000

Reboil Ratio
5.6907

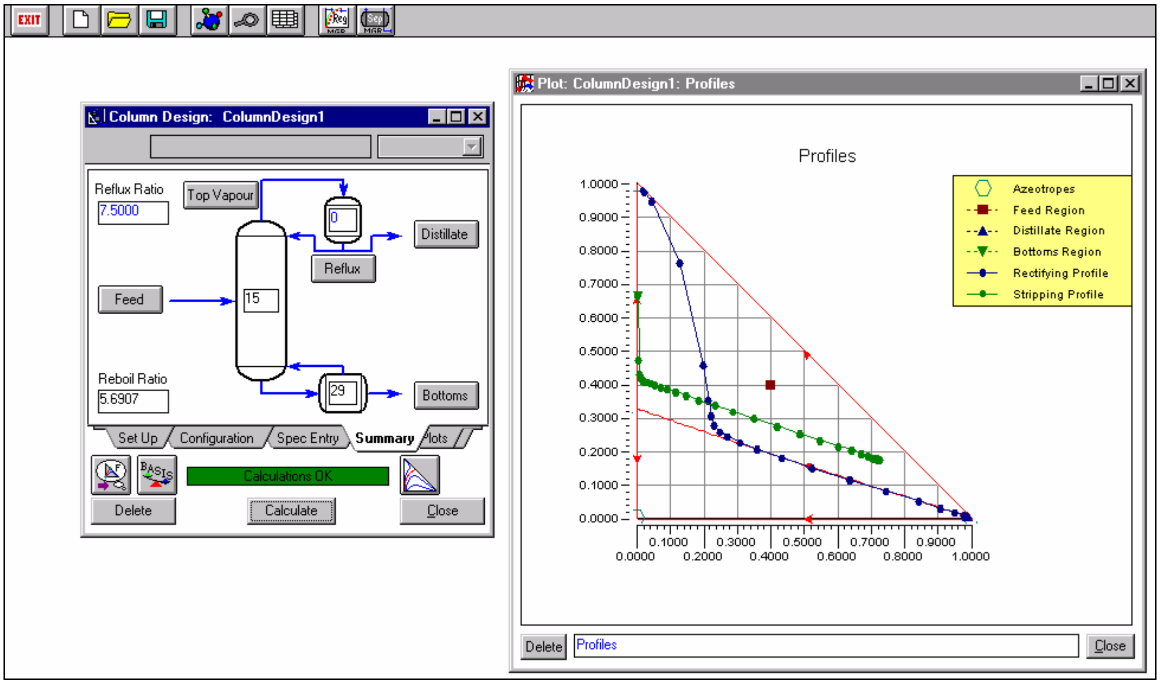
0

6

28

Profiles

Figure 7. Base case design for Part 1.



Column Design: ColumnDesign1

Reflux Ratio 7.5000

Reboil Ratio 5.6907

Calculations OK

Plot: ColumnDesign1: Profiles

Figure 8. Minimum water composition in the distillate is 3400 ppm.

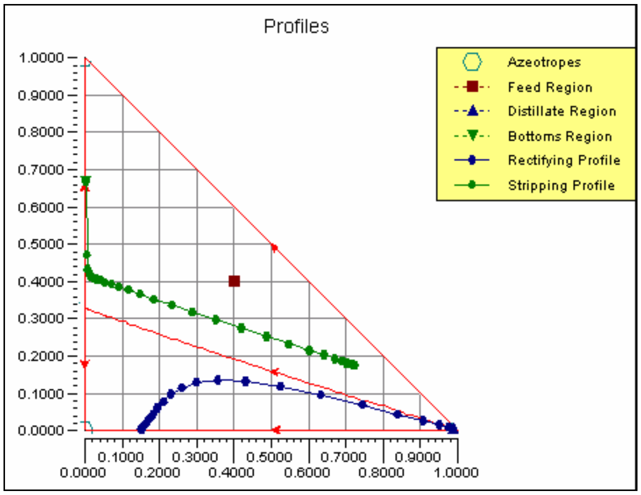
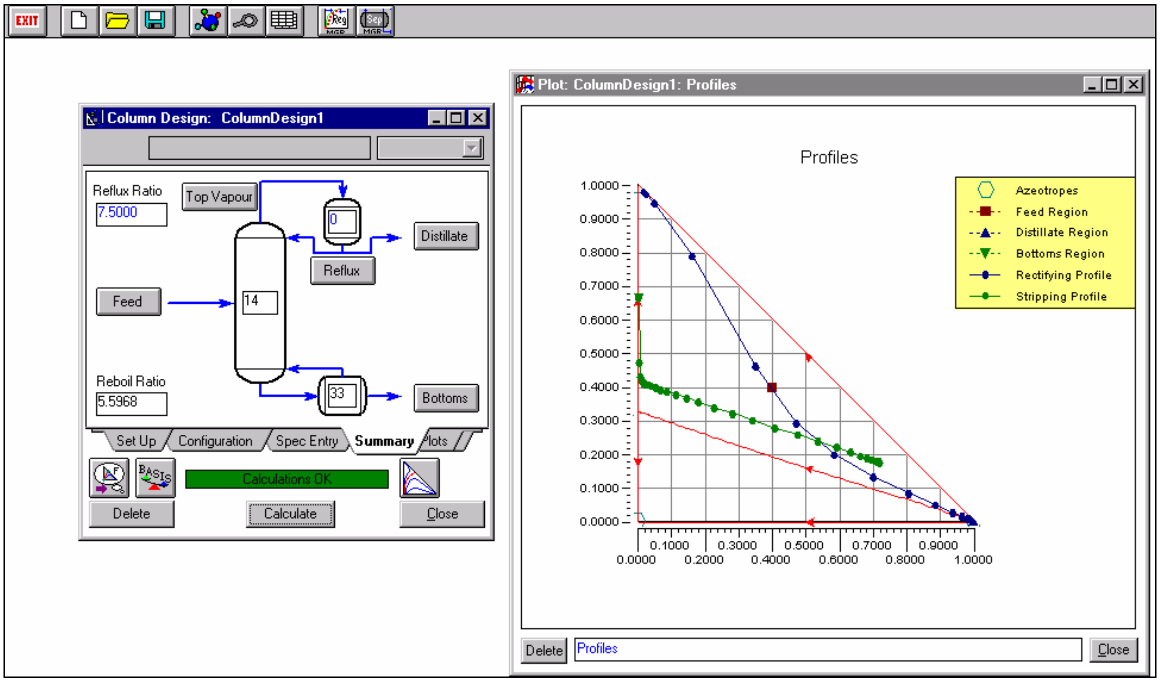


Figure 9. Water composition in the distillate is 3300 ppm, which is below the minimum value.

The solution was developed interactively with the audience at the conference. As was typical of our class experience, many alternative strategies were suggested at the conference within the exact constraints stated in the problem definition. Most alternatives involved adding more columns or other finishing separation steps.

However, the key to achieving our goal is to get the distillate below the distillation boundary into the 50 ppm water range. The best way to do this is to recognize that as the distillation boundary approaches the pure methanol vertex it becomes tangent to the base of the triangle, i.e., free of water. Therefore, we cannot get below the distillation boundary at 99 mol% methanol but we can drive the water content down by *increasing* the purity of the methanol product. The only remaining engineering issue is, how many extra stages are required to do this? Trying a methanol purity of 99.9 mol% does not do it, but 99.99 mol% does! The design is shown in Figure 10 where a 33 stage column operating at the same reflux ratio as the previous (unsuccessful) design achieves a methanol purity of 99.99 mol% and a water content of 50 ppm. Perhaps we can even charge a premium price for our methanol because it is of such high quality. The important lesson to be learned here is that we have achieved our manufacturing goal by relaxing some of the (softer) constraints in order to meet the hard constraint. That is, we have translated the most important part of the customer's order into a *redefinition* of the problem statement. Breaking out of the box is one of the most important aspects of engineering decision-making.



Reflux Ratio 7.5000

Reboil Ratio 5.5968

Figure 10. Column design for distillate stream containing 99.99 mole % methanol, 50 ppm water.

Example 2: Senior Design-Business Challenge Problem

As a two-week module in the Senior Design course, we worked together to provide a realistic business challenge problem, based on GE Plastics experience. We have now used this module two years in a row, with improvements implemented in the second year based on the problems encountered the first year. The students are given the task of taking a plant that is currently losing twenty million dollars a year and turn it into a business making at least five million dollars a year. The flowsheet for this plant has several "opportunities for improvement."

We start the module off with a lecture from our industry partner on business - wide economics. One of the key concepts is telling the students to change the traditional view of profitability from

$$\text{Profit} = \text{Revenue} - \text{Cost}$$

to

$$\text{Cost} = \text{Revenue} - \text{Profit}$$

That is, revenue and profit targets are pre-determined by external forces, i.e., Wall Street, corporate executives or, in this case by the instructors. The students can only manage the cost side of the equation through (1) identifying opportunities to reduce product costs through process analysis (2) funding business activities, such as marketing, to increase demand (3) funding R&D to develop lower cost manufacturing processes or new products with higher average selling prices and/or demand and (4) purchasing additional raw materials to enable the sale of more products. We also describe the basics of an income statement, including revenue, variable costs, base costs, and taxes. We demonstrate the classic basic break-even analysis, shown in Figure 11. If the slope of the total revenue curve is greater than the slope of the variable cost curve then there is some break-even point where the process becomes profitable with increased volume.

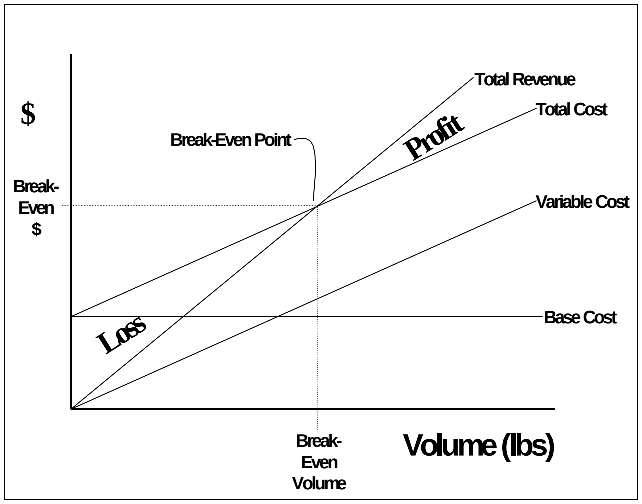


Figure 11. Break-even analysis.

For a problem statement, they receive the following

1. Background information with references to potential investment choices. This contains many details on human interaction, and only careful reading of this will give them instructions on what investments are possible and what investments are wise.
2. A flowsheet of the plant, with incomplete flow and energy information, but enough to allow them to do some mass and energy balances.
3. Last year's budget and income statement.
4. Process chemistry and rate model (as known).
5. An Excel worksheet that simulates the experimental reactor with built-in random error.
6. A budget form with several defined areas for investment, and space for other programs

The assignment is to return a budget statement for the first cycle (1-year) with descriptions of what they expect to achieve with their investments and any instructions they have for modifying the flowsheet. The budget form contained the following investment areas:

1. New business development - look for new business opportunities for the product.
2. Marketing /Advertising - attract new business, maintain, possibly increase price.
3. Manufacturing
   - Process Control and Optimization: Investment above a critical value gives a significant reduction in the noise level of measurements around the reactor. This enables a significantly higher throughput.
   - Base Production Improvements - Reduce general operating costs or increase operating factor
4. R&D Budget
   - New Catalyst Development
   - Catalyst & Reaction Analysis: investment of $1 million in a kinetic model. This enables an accurate calculation of the amount of waste byproduct so that it can be reduced. The reduction in waste costs and ingredient savings exceeds the $1 million investment. Lower levels of investment do not provide the detailed model, but advice that this is a beneficial direction for future investment. However, for this year, this is just a cost with no benefit.
   - New Process Design: specify reactor, process chemistry, and separation systems. One major factor here is in design changes to recycle unreacted ingredients at the optimal level. This generally brings cost benefits in reduced ingredients use well in excess of the cost of implementing the recycle. It is surprisingly difficult for students to identify these seemingly obvious recycle opportunities!
   - Other R&D development - if they put money here without explanation, they just lose it!
5. Other Program Items - for projects they should learn about by careful reading of the problem statement.

This year we added the requirement that they give us the flowrates of each component in the reactor feed to get the production rate they expect. We added this requirement because the first year we taught this module students paid little attention to the flowsheet, randomly guessing on where to invest money.

We used a Microsoft Access database to apply rules for investments and send the information to an Excel spreadsheet with a complete model of the process to determine the income for that cycle. The rules included hidden investments like paying for an environmental evaluation of the plant, which is mentioned in the background information, but not explicitly listed on the budget sheet. If they invested at least $0.5 million in an environmental analysis, they avoided a $5 million fine in the second cycle. This grading could be done in class so the students could prepare a new budget by the next class. We had two breakout rooms with two teaching assistants, who functioned as "corporate experts," in each room to go over the budgets and answer some questions. Then the processed budgets were entered into the computer and the income statement was computed using the database. We had discussions at the beginning of each class talking about the type of decisions made and answering general questions.

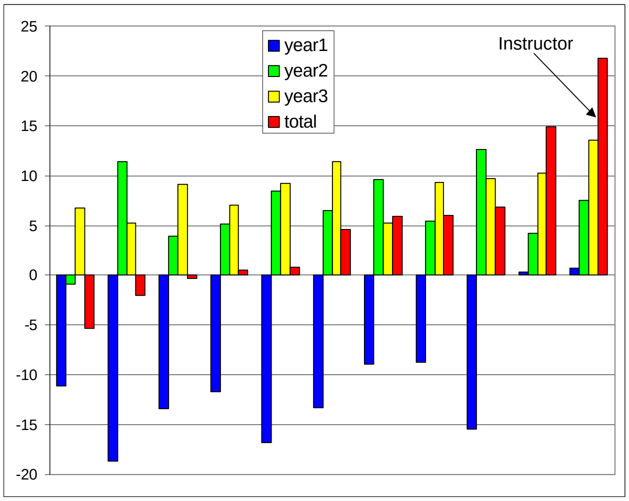


Figure 12. Economic performance for business challenge problem over three yearly cycles.

Figure 12 shows the income for each group over a three-cycle period and the total income for three cycles.

The groups are ordered from left to right by the total income, with results from our own budgets getting the highest ranking. The instructor budgets made all good choices, but not the best possible. Also, it was possible to make more money in a particular year, but that does not necessarily lead to the best long-term results.

The best performing student groups combined elements of chance and common sense (just like the "real world") with engineering judgement. For example, if a group invested sufficiently (perhaps even on the first cycle) to get an optimization and control system on their reactor flowrates, they would produce as closely as possible to the demand. If they realized that some of the raw materials were not being recycled (the smart groups made this observation the first cycle), they would significantly reduce their materials costs.

Most groups lost money the first year because they did not meet demand, because they could not meet it with the current plant, or because they underspecified the flowrates to the reactor. Most groups used the initial values in the Excel spreadsheet we gave them to simulate the test reactor, which was no where near the capacity of the real process reactor.

The poorest performing groups did not carefully read the problem statement and failed to invest in important areas. Another common problem was for a group to continue investing heavily in an area that has already given a great benefit, like new catalyst development, or process control and optimization.

After our first year of teaching this module, we learned that we needed somehow to remind the students to think about the process. The requirement for them to give us the flowrates to the reactor did not help them make more money, since most groups specified flowrates well below the capacity of the reactor, but it did increase the number of groups implementing recycles. After the second year of teaching this module, we have decided to provide the problem statement as hypertext rather than a printed sheet, so we can provide them with extra information. This way we can explicitly tell them what all the possible investments are without making these choices obvious.

Evaluation

A detailed evaluation of the program impact for the 1997-1998 academic year was done by a third-party sub-contract.[2] The primary evaluation goals were to provide formative feedback to the faculty in support of ongoing program improvement, and to assess the extent to which program goals are attained.

There are three primary evaluation questions:

1. To what extent do faculty integrate the technology in the classroom and recent research within the framework of their curricula and teaching styles?
2. What is the affective impact on students of classroom use of the technology? (e.g., attitudes re: the course, subject matter, and discipline)
3. What is the cognitive impact on students? (e.g., mastery of subject matter, problem-solving performance, course grades)

To address these questions, the evaluation used both quantitative and qualitative data sources, using a variety of data collection methods for each area. These include classroom observation, utilization logs (instructor and system), faculty interviews, student focus groups, end-of-semester course evaluations, focused student surveys, and course grades.

During the first year, the amount of class time devoted to student use of workstations differed considerably among courses. In courses with high utilization, students worked at stations approx. 20-25% of the time. In other courses, workstations were only used approximately 5% of the time. The major factors affecting first year utilization include the availability of relevant and reliable software, faculty familiarity with tools, and the time required adapting curricula and teaching styles.

Concerning student attitudes, we found that standard course evaluations, which would enable longitudinal tracking of courses, are unreliable measures of change. However, student interviews and focused surveys indicate positive perceptions of the classroom as a teaching tool, cooperative work with classmates and the benefits of work with software at workstations. Students consistently report a positive impact on their interest in the subject matter and in chemical engineering.

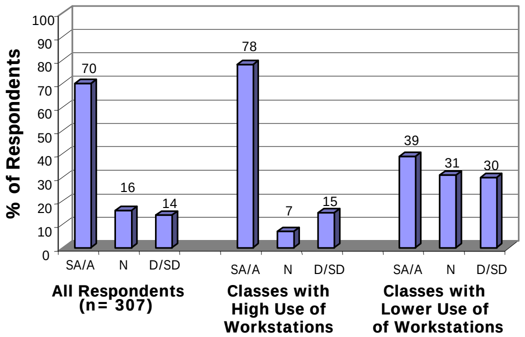


*Figure 13. Student responses to "Use of the technology helped me learn the material more than I would have otherwise." The scale: **S**trongly **D**isagree, **D**isagree, **N**eutral, **A**gree, **S**trongly **A**gree; also applies to subsequent figures.*

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[2] The Maurice A. Donahue Institute for Governmental Services is the public service and outreach unit of the University of Massachusetts President's Office, offering services involving economic and organizational development.

Specifically, 307 student responses were collected which could agree or disagree with the statement “The Alumni Classroom’s technical capabilities helped me to learn more than I would have otherwise." The scale used was Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree with the results shown in Figure 13. The responses of the same group to a similar question statement concerning the quality of learning were essentially identical.

Perhaps the most striking results from student surveys were in the reported effects of the approach on motivation. Student responses concerning motivation through use of technology is shown in Figure 14.

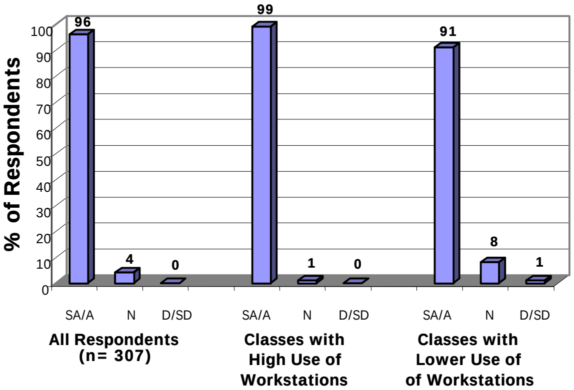

Figure 14. Student responses to “The Alumni Classroom’s technical capabilities motivated me to learn better than in other classes”

Significant changes are found between the first and subsequent offerings of a course using this approach. In fact, the differences correlate more strongly with the experience of the instructor than with the particular course.

The more interesting results concern the percentage of time spent using the technology (Fig. 15) and the correlation with student evaluations of amount of learning (Fig. 16), motivation (Fig. 17) and impact on learning how to solve open ended problems (Fig. 18).

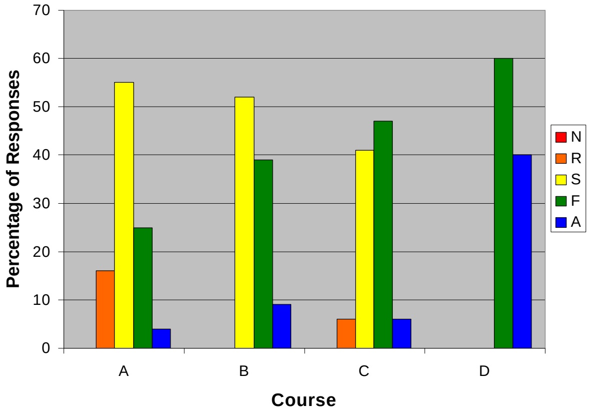

*Figure 15. Student Response to “How often did you work on a computer during class time?” Scale: **N**ever, **R**arely, **S**ometimes, **F**requently, **A**lways.*

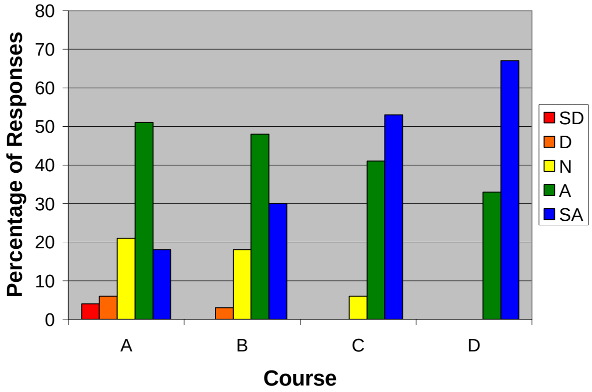

*Figure 16. Student response to “Use of the classroom’s technical capabilities helped me learn the material in this course better than I would have otherwise.” Scale: **S**trongly **D**isagree, **D**isagree, **N**eutral, **A**gree, **S**trongly **A**gree; also applies to subsequent figures.*

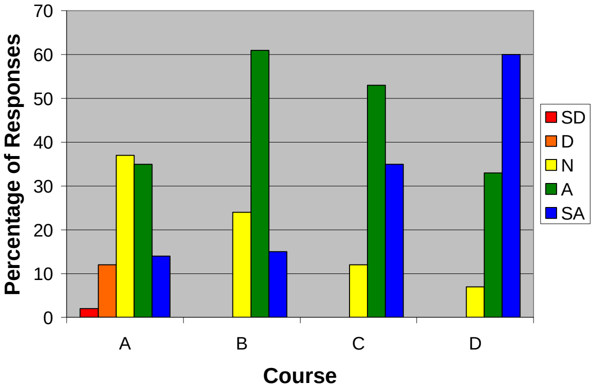

Figure 17. Student response to “Because of the classroom’s technical capabilities, I was more motivated to learn in this class than in others.”

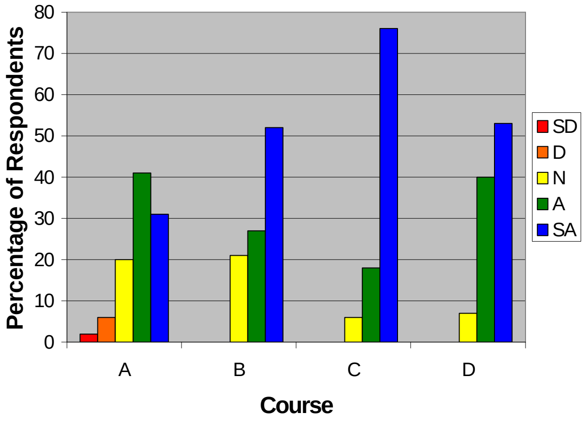

Figure 18. Response to "Use of the facilities contributes more to learning open ended problem solving skills than a traditional classroom."

Summary and Lessons Learned

We have found several important factors for implementing an interactive curriculum and technology.

Essential items:

1. The faculty must have the enthusiasm and release time to change from the traditional lecture format. They must be willing to adapt during class to student discoveries and interests.
2. Software tools must be familiar to the faculty and teaching staff, *before* the class starts.
3. Examples must be developed and tested in the working environment *before* classes.
4. A minimum amount of professional staff time is needed to maintain the computer systems, and for faculty/TA training and support.

Strong Preference:

1. Commercial software unless critical functionality is not available.
2. Team-teaching is advantageous, especially if one of the faculty is experienced with the technology and the other(s) not.
3. The first offering of a course in the new format should be taught by faculty with research experience in the subject and with experience in the software tools used.
4. Industrial involvement is important to let the students know they are learning about real world problems, and to demonstrate the kinds of interactions which occur in industry.

Needs

1. *Component software* and standards to develop, test and distribute tools with new functionality. Preferably Web-based.
2. Easy to use cost models
3. Faster transport models, e.g., for heat transfer and CFD

Acknowledgements

Financial support from the GE Fund and from alumni for construction of the classroom facility is gratefully acknowledged. We are also grateful to P. R. Westmoreland, S. C. Roberts, Z. Q. Zheng, M. Sutherland, K. M. Ng, R. L. Laurence, A Nagurney, and all of our students for their work in the classroom. E. Heller, H. Gibson and S. Liebowitz from the Donahue Institute collected and analyzed data for the evaluation. We are also grateful to the members of our Industrial Advisory Board from GE Plastics, BASF, Dow Corning Corp, DuPont Company, Eastman Chemical Company, Mitsubishi Chemical, Rohm & Haas, Shell International Chemical, Union Carbide Corporation, Unilever Research, Searle, Hyprotech Ltd., and UOP for their extensive comments and suggestions on the content and approach. We are also grateful to AEA Software Technology for HYSYS and HYCON licenses.

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