TWO UNDERGRADUATE PROCESS MODELING COURSES
Taught Using Inductive Learning Methods

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Application of process models in the process industries has increased enormously in the past two decades. Significant advances in computer hardware and software, process modeling, and numerical methods have made possible the sharp rise in the development and application of process models. Among these advances, the availability of increasingly fast computers at very low prices stands out. Process models are currently used in process design, process optimization, model-based control, process monitoring, trouble shooting, safety and flexibility analyses, design of experiments, and personnel training, among other areas. With an increasing use of process models in the process industries, changes have been made in our chemical engineering undergraduate curriculum to equip graduates with adequate process-modeling skills.

Efforts have also been made in other chemical engineering departments and engineering disciplines to respond to the increasing use of process models in the process industries. Foss and Stephanopoulos[1] developed an approach to process modeling in which students are led to crafting a process model before writing any equations. To this end, students are led through a structured modeling methodology with which the physics and phenomena of the process are identified and engineering science concepts placed into a model structure using their developed software. High and Maase[2] developed a graduate process modeling course that involves using MATLAB, which students need to solve equations governing process models. Their course uses case studies, active problem solving, teamwork, and experimentation to promote creative and critical thinking in the students. Nocito-Gobel, *et al.*,[3] developed a multidisciplinary modeling course on mathematical modeling. Pang[4] proposed teaching chemical engineering concepts using plant models. Rappin, *et al.*,[5] developed a software tool that allows students to model and simulate chemical engineering processes. Rabb and Chang[6] described an interdisciplinary dynamic modeling and control course with students and instructors from several engineering disciplines. Layton[7] used modeling and simulation projects to improve learning objectives in a course on systems dynamics.

Inductive teaching methods have received more attention in recent years. In inductive teaching, specific observations, case studies, or examples are presented first, and the general theory is then taught or discovered by the students with the instructor's help after the need to know the theory has been

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established.[8] Inductive teaching methods include project-based learning, case-based teaching, discovery learning, inquiry learning, problem-based learning, and just-in-time teaching. Inductive methods have been found to be in general more effective than traditional deductive methods, in which theories are first given, followed by applications of the theories.[8] Active learning methods,[9] which actively engage students in the learning process, are increasingly used in classes. In contrast, in traditional learning methods, students receive information from the instructor passively. The two courses described herein employ both active learning and inductive methods.

This manuscript describes two core chemical engineering courses, each four quarter-credit hours, that were developed and introduced into the Chemical Engineering Undergraduate Curriculum at Drexel University in 1996. The objectives were threefold: first, to fill the gap that existed between the mathematics courses taken during the freshman year and the chemical engineering courses taken in the following years; second, to improve engineering judgment of chemical engineering students; and third, to provide the students with a strong, lasting background in process modeling that enables them to attack and solve open-ended process modeling problems systematically. The two courses, Process Modeling I and II, have proven successful in achieving the aforementioned objectives. They have been offered in pre-junior and junior years (Years 3 and 4 of our 5-year undergraduate program), respectively; the students take the first modeling course after they have just taken Material and Energy Balances. Some 95% of Drexel undergraduate chemical engineering students select a five-year program including one and one-half years of co-op experience in industry. The open-ended nature of homework problems and the richness of lecture contents, including simple, physically meaningful examples from different disciplines, are among the major features of the two courses. These two courses differ from previous courses taken by the students in several aspects, but perhaps the most important is that the students derive equations from physical problem descriptions, rather than plug numbers into previously derived equations. This equation derivation task represents an active learning process,[9] which requires the students to make a number of engineering judgments to solve process modeling problems in class. Many students view this as a major challenge initially in Process Modeling I, but they soon meet the challenge. The students' in-class activity and engagement in solving modeling problems included in lectures represents an active learning process.

This paper is organized as follows. Section 1 describes common features of the two courses. Sections 2 and 3 then explain the specifics of Process Modeling I and II, respectively. Assessment data and sample students' comments on the courses are included in section 4. Finally, concluding remarks are given in section 5.

1. INSTRUCTION METHOD

An instruction method that is flexible, interactive, and hands-on is used in the two courses. The key instruction focus in these courses is in-class learning rather than covering a priori-set amount of topics in a lecture. In lectures, students think through concepts, solving a set of simple, carefully chosen and arranged, physically meaningful problems. Students actively and directly participate in in-class problem-solving efforts, either individually or as a team (students decide), although they may work at their own rate. Process Modeling I students do this by applying process modeling knowledge or skills learned earlier in Process Modeling I, and Process Modeling II students by knowledge gained in Process Modeling I, Process Modeling II, and other previously taken chemical engineering courses. Note that the same method of process modeling taught in Process Modeling I is used in Process Modeling II. Mathematics is kept in the background until model predictions are needed; it comes into play when process-model equations should be solved to predict the process behavior. The only partial differential equation solved in Process Modeling II is that of a semi-infinite body, for which there exists a closed-form analytical solution in terms of an error function. These courses are offered twice each year, as Drexel has four quarters in each year. Process Modeling I is offered in Fall and Spring Quarters, while Process Modeling II is offered in Winter and Summer Quarters. The number of students in each class ranges from 25 to 40.

Students solve process modeling problems in class without the instructor's direct guidance. The instructor often serves as a "referee" in the class discussions and provides hints in the form of questions (if such hints are necessary). After most students have gone through all of the process modeling steps, one or more student volunteers are chosen by the instructor to write their solution(s) on the board. Other students are then asked to evaluate the correctness of the process model(s) written on the board. The volunteer students should explain, defend, and correct their model(s), if a correction is necessary. At the end of each process modeling problem, the instructor summarizes the class discussions to highlight the key concepts in the problem.

2. PROCESS MODELING I

This course begins with a review of the applications of process models in the process industries and a description of a mathematical model; that is, a set of equations that describe the relations among relevant variables (that are of interest to the user) in a process. The rest of the course is devoted to how to derive the set of model equations by taking students through derivations of model equations for about 50 process examples carefully selected from several disciplines. Some of these examples are listed in Table 1. Each process model has four main components:

I. *Conservation equations*

II. *Constitutive equations*

III. *Constraints on process variables*

IV. *Conditions for the dependent variables*

In developing macroscopic models, the conservation laws (species, mass, momentum, and energy), which serve as the main pillars of the models, are closed through constitutive equations (*e.g.*, reaction rate equations, ideal gas law, Fick's law of diffusion, Fourier's law of conduction, Newton's law of viscosity, and Stefan-Boltzmann law of radiation). Given the same input (information) that is provided for the process under consideration, these equations should allow one to describe/predict the process behavior of interest. Constraints on process variables define the regions in which process model predictions are physically meaningful; they provide the model equations with additional physical and chemical realities. For example, a steady state model, consisting of a set of algebraic equations, can have a solution with a negative steady state concentration, which is not physically meaningful. The constraints are also helpful in solving the model equations numerically. The conditions allow one to solve governing differential equations and predict uniquely the process behavior. Principal topics covered in lectures include:

- *Macroscopic first-principles models for simple lumped-parameter dynamic processes*
- *Steady state behavior*
- *Numerical solution to a set of algebraic equations (Newton-Raphson and secant methods)*
- *Macroscopic first-principles models for simple spatially distributed steady state processes*
- *Numerical integration (Euler's, implicit modified Euler's, and explicit modified Euler's methods)*
- *Compartmental modeling of spatially distributed processes*
- *Lumped-parameter modeling of processes with imperfect mixing*

Coverage of these numerical methods ensures that all students have adequate knowledge of those algorithms behind equation solvers available on computers. Students in Process Modeling II use computers extensively to solve model equations numerically.

The roughly 50 examples covered during lectures are carefully selected from several different disciplines and arranged in a proper sequence, so that each example is used to teach a concept that is required in process model development of a subsequent example. A list of some of these examples is given in Table 1. The examples' diversity emphasizes to the students that the modeling method is systematic and general; that is, the method can be applied to any process, whether it is a chemical plant, the human body, or a collection of living organisms.

Process Modeling I is offered before Fluid Dynamics, Mass Transfer, Heat Transfer, and Reaction Kinetics. An inductive teaching method[8] is used in this course. The constitutive equations needed in Process Modeling I but taught in detail later in these four chemical engineering courses are derived in Process Modeling I by calling on the students' intuition. Their intuition is invoked frequently to derive the functional or specific form of the constitutive equations that the students have not seen previously. For example, the functional form of a constitutive equation describing the dependence of flow rate of a fluid inside a pipe on pressure difference between the two ends of the pipe, length, roughness, and diameter of the pipe, and fluid viscosity, is derived via intuitive qualitative prediction of the effects of fluid and pipe properties and pressure difference between the two ends of a pipe on the flow rate of a fluid through the pipe. A specific (linear) form of the constitutive equation is derived using the analogy between flow of a fluid (driven by pressure difference) through a pipe and electric current (driven by electric potential difference) through a resistor. Students who take Process Modeling II are already familiar with different flow regimes and correlations for pressure drop in a pipe, as they take this course after the Fluid Dynamics course. This intuitive approach is needed only in Process

TABLE 1
Sample Process Examples Covered in Process Modeling I Lectures

Liquid level in a tank with an open top and two pipes at the bottom
Liquid level in a tank with a fixed closed top, trapped gas above liquid, and two pipes at the bottom
Liquid level in a tank with a moving closed top attached to an outside spring, trapped gas above liquid, and two pipes at the bottom
Heating tank
Mixing tank
Stirred tank chemical reactor
Continuous stirred tank fermentor
Tubular chemical reactor
Flow of a river over a salty bed
One-pass, shell and tube heat exchanger
Growth of fish in a lake
Prey and predator example
Female and male populations of a species
Mixing tanks with imperfect mixing
Tank reactors with imperfect mixing
Intravenous (IV) injection (drip) of a drug over a time period (zero order infusion)
IV bolus injection/shot of a drug
Drug shot under skin (subcutaneous injection of a drug)
Oral administration of a drug

Example 1. Consider the tank shown in Figure E1. Develop a model to describe level of water in the tank, h (m), as a function of upstream and downstream pressures (P_1 and P_2). F_1 and F_2 are volumetric flow rates of water (m^3/s) through the two pipes connected to the bottom of the tank. For a moment, let us assume that water flows into the tank through the left pipe and leaves the tank through the right pipe. P $(kg/m/s^2)$ is the pressure at the bottom of the tank. P_g $(kg/m/s^2)$ is the gas pressure at the top of the tank.

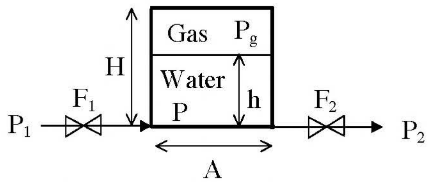

Figure E1: Tank process of Example 1.

Assumptions
Constant tank cross-sectional area (A); No evaporation of water; Air does not dissolve in water; Constant water density (ρ_w); Constant temperature (T); Constant tank volume (AH)

Process Model Development

I. Conservation Equations

– Mass balance on water in the tank

$$F_1\rho_w - F_2\rho_w + 0 - 0 = \frac{d}{dt}[m] \quad (kg \text{ of water}/s)$$

– Mass balance on air in the tank

$$0 - 0 + 0 - 0 = \frac{d}{dt}[m_a] \quad (kg \text{ of air}/s)$$

where m is the mass of water in the tank, m_a is the mass of air in the tank, and t is time (s). The second equation implies that m_a is constant.

II. Constitutive Equations
$m = \rho_w Ah$ (tank has a constant cross-sectional area); $F_1 = f_1(P_1 - P)$; $F_2 = f_2(P - P_2)$; $P = \rho_w gh + P_g$; Ideal gas law (assumption): $A(H-h)P_g = m_a RT/M_a$

III. Constraints

$$h \geq 0, \quad t \geq t_0 \text{ (reference time)}, \quad P \geq 0, \quad P_1 \geq 0, \quad P_2 \geq 0 \text{ (absolute pressures)}$$

IV. Conditions
The model has one 1st-order ordinary differential equation; one condition is needed. For example, $h(t_0) = h_0$.

Process Model

$$A\frac{dh}{dt} = f_1\left(P_1 - \frac{m_a RT}{M_a A(H-h)} - \rho_w gh\right) - f_2\left(\frac{m_a RT}{M_a A(H-h)} + \rho_w gh - P_2\right), \quad h(t_0) = h_0$$
$$h \geq 0, \; t \geq t_0, \quad P \geq 0, \; P_1 \geq 0, \; P_2 \geq 0$$

Given the pressures $P_1(t)$ and $P_2(t)$, the model can predict $h(t)$.

Figure 1. *Sample Process Modeling I lecture notes (size reduced)—Part I.*

Modeling I, which is offered before our chemical engineering undergraduate courses except for Material Balance.

The interactive hands-on learning approach implemented in Process Modeling I is described using the two sample examples from Process Modeling I lecture notes given in Figures 1 and 2. Roughly a one-hour lecture is devoted to solving one to two of such process modeling problems. First, the instructor describes the process modeling problem using a schematic of the process. Second, to help students understand the problem, the instructor asks students to predict qualitatively and sketch the responses of the process variables—which the model should predict—to changes in other variables of the process. For example, the instructor asks them to predict whether water level in the tank of Example 1 or 2 (Figure 1 or 2) rises or drops when the downstream pressure increases. Third, the instructor asks students to develop a model of the process (carry out steps I-IV listed at the beginning of this section). Students can discuss their ideas with each other and the instructor. The instructor "answers" questions and interacts with students through asking questions; direct answer is not provided. Fourth, one or two students voluntarily come to classroom board and write their solution(s) on the board. A reward (1-3 points) is given to the students who come to the board. The points are counted towards 5% of the final grade. If no student is willing to come to the board, the instructor solves the trivial parts of the process modeling problem and then increases the level of the reward (number of points) and allocates more time to the problem, until one student volunteers to solve the challenging part(s) of the problem. Fifth, the instructor asks the sitting students to comment on the correctness and completeness of the solution(s) written on the board. The standing student(s) should answer the questions without any instructor's interference. If the solutions written on the board are incorrect or incomplete and the seated students cannot detect these deficiencies, then the instructor asks questions that indirectly point to the deficiencies in the solution(s). Finally, the instructor provides a summary of key issues in the process-model development after a complete and correct process model is developed.

Leading students through derivation of model equations for about 50 carefully selected process examples in the lectures allows the students to improve their engineering judgment and to learn how to systematically integrate information on a process to form a process model. Students' grades in Process Modeling I are based on scores in three exams, each with a weight of 28%, and on homework scores. The students are provided with typed lecture notes; notes for a week of lectures are made available to students in the following week (only after the lectures are given). Several textbooks[2-4] are recommended as references for background information.

TABLE 2 Sample Examples Covered in Process Modeling II Lectures
Transient temperature profile in a semi-infinite solid
Transient temperature profile in a cylindrical solid
Transient temperature profile in a spherical solid
Liquid level in two tanks (with significantly different cross sectional areas) in series
Arnold cell
Batch reactor with two series reactions of significantly different rates
Aging of human vs. that of a fly
Profile of temperature inside a fin
Transient concentration profile inside a solid sphere

TABLE 3 Process Modeling II Sample Projects
Position vs. time behavior of bouncing ping-pong and golf balls
Free fall of Teflon and metal spheres in a sugar solution
Water drainage from a tank
A bottle of perfume
A layer of oil on a large area of flat land
Evaporation of water in a graduate cylinder
Liquid chemical spill on a sea

Example 2. Consider the tank shown in Figure E2. Develop a model to describe level of water in the tank, h (m), as a function of upstream and downstream pressures (P_1 and P_2). F_1 and F_2 are volumetric flow rates of water (m^3/s) through the two pipes connected to the bottom of the tank. For a moment, let us assume that water flows into the tank through the left pipe and leaves the tank through the right pipe. P $(kg/m/s^2)$ is the pressure at the bottom of the tank. P_g $(kg/m/s^2)$ is the gas pressure at the top of the tank. m_t (kg) is the mass of the tank top.

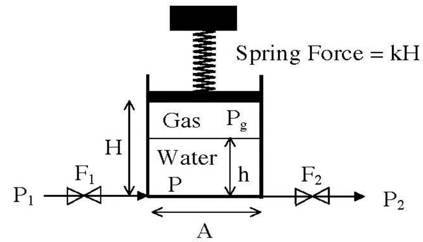

Figure E2: Tank process of Example 2.

Assumptions
Constant tank cross-sectional area (A), No evaporation of water, Air does not dissolve in water, Constant water density (ρ_w), Constant temperature (T), Friction-free tank top

Process Model Development

I. Conservation Equations

– Mass balance on water in the tank

$$F_1\rho_w - F_2\rho_w + 0 - 0 = \frac{d}{dt}[m] \quad (kg \text{ of water}/s)$$

– Mass balance on air in the tank

$$0 - 0 + 0 - 0 = \frac{d}{dt}[m_a] \quad (kg \text{ of air}/s)$$

where m is the mass of water in the tank, m_a is the mass of air in the tank, and t is time (s). The second equation implies that m_a is constant.

– H is not constant in this example and denotes the position of the top. Momentum balance along H for the top:

$$p_g A - m_t g - kH = \frac{d}{dt}\left[m_t \frac{dH}{dt}\right] \quad (kgm/s^2)$$

II. Constitutive Equations
$m = \rho_w Ah$ (tank has a constant cross-sectional area); $F_1 = f_1(P_1 - P)$; $F_2 = f_2(P - P_2)$; $P = \rho_w gh + P_g$; Ideal gas law (assumption): $A(H-h)P_g = m_a RT/M_a$

III. Constraints
$h, H \geq 0$, $t \geq t_0$ (reference time), P, P_1, $P_2 \geq 0$ (absolute pressures)

IV. Conditions
The model has one 1st-order and one 2nd-order ordinary differential equations; three conditions are needed. For example, $h(t_0) = h_0$, $H(t_0) = H_0$, $dH/dt|t_0 = 0$.

Process Model

$$A\frac{dh}{dt} = f_1\left(P_1 - \frac{m_a RT}{M_a A(H-h)} - \rho_w gh\right) - f_2\left(\frac{m_a RT}{M_a A(H-h)} + \rho_w gh - P_2\right), \quad h(t_0) = h_0$$

$$m_t\frac{d^2H}{dt^2} = \frac{m_a RT}{M_a A(H-h)}A - m_t g - kH, \quad H(t_0) = H_0, \quad dH/dt|t_0 = 0, \quad h, H, P, P_1, P_2 \geq 0, \quad t \geq$$

Given the pressures $P_1(t)$ and $P_2(t)$, the model can predict $h(t)$.

***Figure 2.** Sample Process Modeling I lecture notes (size reduced)—Part II.*

3. PROCESS MODELING II

Process Modeling II complements Process Modeling I. It uses the same systematic method to develop mathematical models of more complex processes. Topics covered in the lectures include:

- *Use of dimensionless and normalized variables in models*
- *Functional form of solutions to model equations and design of experiments*
- *Steady states and steady state multiplicity*
- *Asymptotic stability (AS) and AS analysis of a steady state*
- *Multi-time-scale processes, quasi-steady state (QSS) assumption, QSS model, and fast model*
- *Spatially distributed dynamic processes*
- *Method of combination of variables*

As in Process Modeling I, many carefully chosen process examples from different disciplines are used to teach the topics listed above. Table 2 presents a list of sample process examples covered in Process Modeling II lectures.

Each week a process modeling project is assigned to students. The titles of several sample projects assigned in Process Modeling II are listed in Table 3. In most of these projects, students are provided with data (measurements) or are taken to a lab to conduct experiments and collect (make) data (measurements). They use the data (measurements) to perform model-parameter estimation and evaluate the quality of their model predictions. The process modeling project reports should include all of the

TABLE 4
Building Blocks of a Process Modeling II Project Report

1. Describe the process modeling problem accurately
2. Understand the problem
a. Collect information
b. Do bounding calculations
c. Draw a picture of the entire process
d. Identify the process variables
3. Derive process model equations
a. Draw schematic of systems and subsystems
b. Write down notations
c. Choose assumptions
d. Write down relevant axiomatic laws
e. Write down relevant constitutive equations
f. Assemble and simplify model equations
g. Write down constraints, and boundary and initial conditions
4. Solve the model equations
a. Select a solution method (analytical or numerical)
b. Implement the solution method
c. Evaluate the adequacy/reliability of the numerical solution
5. Perform parameter estimation to calculate the model parameters
6. Present model predictions (plots and/or tables)
7. Evaluate the accuracy of the model predictions
8. Discuss the results

TABLE 5
Student self-assessment of Process Modeling I course-objectives collected over 14 quarters, Fall Quarter 00-01 to Spring Quarter 06-07 (5=expert, 4=good, 3=fair, 2=poor, 1=no experience); Number of students responded = 160; Number of students not responded=251.

		Average	Standard Deviation
Identifying fundamental phenomena governing a given process	Entering this course	2.46	0.92
	Leaving this course	4.05	0.59
Writing relevant balance equations	Entering this course	3.13	0.84
	Leaving this course	4.23	0.60
Developing mathematical models for chemical processes	Entering this course	2.23	0.86
	Leaving this course	4.10	0.65
Solving mathematical model equations governing a process	Entering this course	2.67	0.91
	Leaving this course	3.96	0.70

TABLE 6
Student self-assessment of Process Modeling II course-objectives collected over 12 quarters, Winter Quarter 00-01 to Summer Quarter 05-06 (5=expert, 4=good, 3=fair, 2=poor, 1=no experience); Number of students responded = 155; Number of students not responded=221.

		Average	Standard Deviation
Developing a mathematical model for a process that you had not seen before	Entering this course	3.09	0.69
	Leaving this course	4.04	0.61
Evaluating the accuracy/adequacy of a process model that you developed	Entering this course	2.84	0.81
	Leaving this course	3.98	0.73
Writing a technical report on a process modeling project that you carried out	Entering this course	3.39	0.84
	Leaving this course	4.10	0.69
Identifying and presenting efficiently the main results of a process modeling project	Entering this course	3.03	0.80
	Leaving this course	4.08	0.67

components listed in Table 4. Presentation quality of the report is also very important. The report should show clearly and concisely a) the work performed to develop the model, b) the prediction capabilities of the model, and c) an evaluation of accuracy/reliability of the model predictions. The final grade is based on the project scores (weight of 45%), two exam scores (weight of 25% each), and the 5% performance (points collected in the class). As in Process Modeling I, the students are provided with typed weekly lecture notes with a one-week delay, as no appropriate textbook is currently available for this course, either. Several textbooks[10-13] are recommended as references.

4. COURSE ASSESSMENT AND STUDENTS' COMMENTS

At the end of the week in which each course ended, an e-mail was sent to each enrolled student to ask the student to complete an online evaluation form. The survey was anonymous. Each of the online evaluation forms included questions on the course objectives. For Process Modeling I, the course objectives were:

- *Identifying fundamental phenomena governing a given process*
- *Writing relevant balance equations*
- *Developing mathematical models for chemical processes*
- *Solving mathematical model equations governing a process*

and for Process Modeling II:

- *Developing a mathematical model for a process that you had not seen before*
- *Evaluating the accuracy/adequacy of a process model that you developed*
- *Writing a technical report on a process modeling project that you carried out*

TABLE 7
Sample comments made about Process Modeling I and II by students after graduation

"How do you blend science, experiment, casual observation, and common sense to predict the behavior of a system? How do you use both the art and science of engineering to solve a problem? Process Modeling I and II approached these questions and in doing so served as an integral piece of the chemical engineering curriculum. In particular, Process Modeling benefited students by: 1) offering a general systematic problem-solving methodology; 2) depicting purpose for mathematics in engineering; and 3) being taught through a flexible, hands-on approach."
"The only courses taken prior to Process Modeling I were Material and Energy balances. While both courses were obviously invaluable to a chemical engineer, they focused on simple approaches to a narrow scope of problems. Process Modeling I offered a systematic, general problem solving approach to modeling any system. *"Such an approach allowed young chemical engineering students to model systems involving momentum, mass, and heat transfer without formally beginning the transport sequence. Reaction kinetics and reactor design are explored years before students take the formal course. An inductive approach to looking at constitutive equations is used—through which students gain a qualitative rather than scientific grasp on the concepts."*
"Process Modeling I was a very good introduction to modeling techniques as well as methods to solving algebraic and differential equations. It incorporated aspects and examples found in other chemical engineering courses such as Material and Energy Balances and the transport courses. The course approached problems in a very systematic way, making it easier to define, outline, and set up problems."
"Engineering students are generally required to take multivariable calculus and differential equation courses prior to beginning their engineering studies. Eventually students start questioning the usefulness of mathematics in their studies. Process modeling shows students how mathematics is nothing more than a body of knowledge that engineers tap into to help perform their work. *"In Process Modeling I and II, few problems are analytically solved. Rather, students build quick dynamic models (which are solved numerically in homework assignments). This approach keeps the focus of the course on modeling rather than solving."*
"The professor's teaching style complements the nature of the course. Rather than typical professor-to-students teaching, an interactive hands-on learning approach is encouraged. A significant portion of the class is devoted to solving in-class problems (without the professor's immediate guidance). Most chemical engineering courses would immediately become more valuable by adopting such an approach. Simple concepts become needlessly difficult to students because the basics were overlooked."
"Process Modeling II expanded on the previous course and went further in depth. It, too, took a systematic approach to solving problems. It highlighted the importance of dimensionless variables and developed methods for solving partial-differential equations. A significant amount of time was spent on the analysis of steady states and stability."
"Process Modeling I and II provided a solid framework for modeling any process as well as preparing the student for higher-level chemical engineering and math courses. Both courses helped me in analyzing problems by knowing how to determine the fundamental issues, simplify and lump systems, evaluate relative rates of change, and apply known laws and concepts to come to a conclusion."
"Process Modeling I was the class I liked the most during my undergraduate study at Drexel. It helped me to defeat my fear when I encounter a problem that I haven't seen before. It taught me all the steps on how to attack a problem that looks complicated. In this class, I learned that nothing is too intricate in science; all the formulas and equations come from basic simple principles. *"Process Modeling II taught me the importance and the power of different math software such as Mathematica, Maple, and many others. It taught me how to look at things in the big picture."*
"The modeling courses at Drexel provided a core foundation that allowed subsequent courses to build upon. Being able to successfully model a process is integral to the understanding and solving of many systems in the chemical engineering discipline. Compared to other chemical engineering courses at Drexel, I found Process Modeling I and II to be two of the few courses that tie together many of the other coursework including reaction kinetics and all of the transport classes. *"While studying with other students for Ph.D. qualifying exams it became apparent that other universities do not stress the importance of modeling processes, but instead focus more on a quantitative approach. Without fully understanding the purpose of modeling it is difficult to attack unfamiliar problems. I feel that having taken these classes has absolutely raised my confidence level and understanding of problems I haven't seen prior."*

- *Identifying and efficiently presenting the main results of a process modeling project*

The assessment results collected over seven and six years for Process Modeling I and Process Modeling II, respectively, are given in Tables 5 and 6. The second column from the left in each of the two tables lists the average of the "entering" and "leaving" scores given by students for each course objective. The difference between entering and leaving average scores for each course objective is a measure of the impact of the course on the students in terms of the specific course objective. Overall, the assessment results confirm the effectiveness of the courses in transferring knowledge from the instructors to the students.

Sample comments made by students who already took Process Modeling I and II and graduated, are listed in Table 7. The students wrote and sent these comments to the instructor in response to a request by the instructor, as part of the end-of-course instructional survey. Before including these comments in this paper, the authors edited a few of the comments to take care of a few spelling/grammatical errors therein. In addition to the course-assessment data collected right after the courses ended, comments received from students and graduates of our chemical engineering program over the past decade have confirmed that the course contents, the method of delivery, and the "in-course" feedback given to students through evaluation of the students' performance in assigned homework and exams all successfully contributed to the realization of the three course objectives. Notable among the comments are that the courses instill systematic problem-solving skills in the students and show clearly and logically the purpose of mathematics in engineering, using a flexible, hands-on teaching approach. The courses blend science, experiment, casual observation, and common sense to enable the students to predict the behavior of a system.

5. CONCLUDING REMARKS

A successful application of inductive learning in process modeling was presented. Two process modeling courses that use inquiry learning and problem-based learning, among other types, were described. The courses have been very popular among the students and graduates of our chemical engineering program. Students returning from Drexel Co-op have expressed their satisfaction with the techniques they learned in these courses, as they used the techniques or saw the application of the techniques directly in their co-op projects. The graduates who took industrial positions requiring them to develop process models or went to graduate school described how confident they felt when they encountered and solved complex process modeling problems. Both groups have pointed to three significant impacts of the courses: first, the confidence that the courses built in them to attack and solve new process modeling problems; second, the systematic and universal nature of modeling techniques covered and learned in the courses; and third, their ability to remember easily and apply quickly the techniques they learned.

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REFERENCES

1. Foss, A.S., and G. Stephanopolous, "Leading Undergraduates Along Structured Paths to the Building of Good Process Models," *Proceedings of ASEE*, Session 3613 (1999)
2. High, K., and E. Maase, "Active Problem-Solving in a Graduate Course on Modeling and Numerical Methods," *Proceedings of ASEE*, Paper AC 2007-1423 (2007)
3. Nocito-Gobel, J., M. Collura, and S. Daniel, "A Multidisciplinary Modeling Course as a Foundation for Study of an Engineering Discipline," *Emerging Trends in Engineering Education*, Session 1693, Paper 2006-2372 (2006)
4. Pang, K.H., "Teaching Chemical Engineering with Physical Plant Model at Cal Poly, Pomona," *Proceedings of ASEE*, Session 2213 (2001)
5 Rappin, N., M. Guzdial, M. Realff, and P. Ludovice, "Experiments in Learning Chemical Engineering Modeling Skills," *Proceedings of ASEE*, Session 2213 (2001)
6. Rabb, R., and D. Chang, "Interdisciplinary Teaching Techniques and Learning in Dynamic Modeling and Control," *Proceedings of ASEE*, Session 501 (2008)
7. Layton, R.A., "Using Modeling and Simulation Projects to Meet Learning Objectives in an Upper-Level Course in Systems Dynamics," *Proceedings of ASEE*, Session 2320 (2003)
8. Prince, M.J., and R.M. Felder, "Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases," *J. of Engineering Education*, **95**(2), 123 (2006)
9. Prince, M., "Does Active Learning Work? A Review of the Research," *J. of Engineering Education*, **93**(3), 223 (2004)
10. Felder, R.M., and R.W. Rousseau, *Elementary Principles of Chemical Processes*, 3rd Ed., Wiley and Sons (2005)
11. Welty, J.R., C.E. Wicks, G.L. Rorrer, and R.E. Wilson, *Fundamentals of Momentum, Heat, and Mass Transfer*, 5th Ed., Wiley and Sons (2008)
12. Gerald, C.F., and P.O. Wheatley, *Applied Numerical Analysis*, 7th Ed., Addison-Wesley Publishing Co (2003)
13. Perry, R.H., D.W. Green, and J.O. Maloney, *Perry's Chemical Engineer's Handbook*, 7th Ed., McGraw-Hill (1997); <http://www.knovel.com> ❒