AC 2007-79: A STREAM IN PROCESS SYSTEMS ENGINEERING (PSE) IN THE UNDERGRADUATE CHEMICAL ENGINEERING CURRICULUM

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1. Introduction

Process Systems Engineering (PSE) plays a central role in the chemical engineering education and practice. In this paper, we present our experiences with offering an undergraduate stream in Process Systems Engineering to enable students to build expertise in this field. (We will discuss the meaning of a stream later; for now, let's consider it a "minor" within the chemical engineering four-year curriculum.) We believe that a stream offers tremendous advantages to students, namely (1) enabling students to follow their interests, (2) providing experiences in learning in depth, and (3) empowering students to focus their course options and electives. The stream has advantages for faculty as well; for example, faculty can make research strengths accessible to undergraduates and can convey to their students the excitement of studying and applying new technologies.

In this paper, we provide

- An approach to provide focussed course options and electives in a stream, which could be modified for other stream topics
- A recommendation for the division of PSE topics between required and elective courses
- A description of advanced PSE topics and how they can be delivered within the chemical engineering curriculum

We begin by explaining our view of the topics included in PSE stream, with a brief comparison with a few prominent alternative definitions of PSE, and we address the need for a clearly defined stream, rather than a selection of courses. Then, we define PSE learning goals, and present the sequence of courses that address these goals. We demonstrate that the courses include considerable integration and numerous industrial experiences. We conclude by relating experiences from the stream and plans for future enhancements.

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1.1 What do we mean by Process Systems Engineering (PSE)?

Let's establish a definition of Process Systems Engineering. Most academics consider ***decision support*** to be the key feature of PSE. The PSE decision support methods can be applied to an essentially unlimited set of process, environmental, business, and public policy systems. While the opportunities are unlimited, PSE is initially introduced with examples of greatest importance to chemical engineering undergraduates, with course projects and enrichment readings providing extensions to other applications.

The decision support methods we include in PSE are modeling (first principles fundamental and data-based), simulation, process control, applied statistics, optimization, synthesis and design. These topics overlap with many existing courses in engineering, operations research and applied mathematics, so that much excellent teaching and learning material is available. However, a great challenge exists in teaching them at the appropriate undergraduate level, linking to practical engineering applications, integrating the PSE methods into a "systems" viewpoint and providing increasingly complex applications as the students' understanding of engineering increases.

Before discussing the learning goals and curriculum, we note two differences between our viewpoint and that of some other educators. The major distinction is the broad range of topics addressed in the PSE stream. Typically, discussions center on the topic of process control and what should be included (and not included) in the undergraduate course. An interesting recent paper on this topic included input from industrial practitioners, which is summarized in Table 1 from Edgar[1]. Several topics rated most important by industrial practitioners in Table 1, including the top two items (optimization and design of experiments), are not now, and in our view, should not be, included in the process control course. The survey supports the importance of optimization and applied statistics for a chemical engineer; therefore, we have structured a program to introduce these topics in the PSE stream.

We note that we find no difficulty in convincing students of the importance of statistics, since they are aware of challenges involved with experimental design, model building, and quality control. We are a bit dismayed by the lack of statistics in many chemical engineering programs and by the exclusion of the topic in some prominent discussions of PSE[2]. We believe that the consideration of model building and validation and considerations of uncertainty in decision making (e.g., statistical process control, automatic process control and optimization) requires the engineer to have a solid understanding of applied statistics.

The second major difference involves important professional skills, such problem solving, creativity, group skills, and dealing with incomplete and uncertain information. Perkins[3] makes the case for including these topics in PSE. We fully support the importance of the professional skills in the undergraduate program; we introduce these methods in several of our PSE courses; and we integrate them in all courses. However, we note that many of the innovators of teaching these topics in chemical engineering are not from the PSE community[4,5,6,7]. In addition, professional skills can be introduced in many courses, with the choice depending on the teaching interests in individual departments. Therefore, we will not discuss professional skills here as part of PSE, while recognizing their crucial importance for our students.

Finally, one might reasonably ask how our view of PSE compares with a developing proposal for the "Curriculum of the Future" [8]. We are pleased that systems topics play a prominent role in the proposal; however, in our view, the proposal has not yet reached a level of detail to enable a comparison. We can make a few preliminary observations. First, the "Future" includes much more material in the systems category than we are suggesting here. For example, "Future" includes general modeling based on material and energy balances and many topics that we consider professional skills, e.g., ethics, globalization, intellectual property and so forth. While these topics are important, their link to PSE are tenuous; as a result, the systems topic could be diluted into an "everything else" category that would not represent its central importance. Second, the "Future" proposes coverage of molecular level and multiscale topics that require further definition. We will observe the warning that "God (or the devil) is in the details", and therefore, we prefer to wait for much more detail before comparing our current program with the developing proposals for the future.

1.2 Why a Stream in Process Systems Engineering (PSE)?

Chemical engineering is a broad field that is continuing to broaden into biochemistry, nanotechnology, and other emerging fields. As a result, undergraduate students are challenged to gain some knowledge in many topics. This valid diversity in the core chemical engineering program is not entirely consistent with student needs for freedom in selecting some topics for study, reinforcing their learning, building expertise, and having an "identity" related to a field of study more concentrated than chemical engineering. Therefore, we offer a stream of optional courses in PSE that enables students to engage in learning in depth without diluting the core program.

By the term "stream", we mean a concentration of study on an integrated body of knowledge that can be completed without extending the normal undergraduate program beyond four years (eight terms). In some universities, this might be termed a minor. As we will explain, this is achieved by the proper selection of technical electives and in options in a few required courses. The total number of electives required for graduation is not affected by the selection of the stream.

We note that extending the undergraduate program to five years is also popular, for example, for integrating a minor into an engineering education[9]. In fact, about 25 percent of the undergraduate engineering students our university participate in one of a variety of five-year programs. However, we believe that students wishing to pursue further studies in PSE are best served by entering graduate studies, where they can share their experiences with a group of dedicated fellow graduate students.

Perhaps, the question could be raised, "Why a stream at all?" Our answer is based on the observation that students learn best when they have some choice regarding the topics they are learning. As a result, students are more enthusiastic, work harder and learn more while working on a stream that offers new learning opportunities while applying skills from their major. In addition, the students benefit from the opportunity to build a viewpoint that can be applied to nearly all issues in the engineering profession.

Now, why a stream in PSE? The PSE stream builds on the core topics and enables students to concentrate their technical electives on an integrated set of systems topics. Students gain two advantages. First, they build expertise in an important field of engineering. PSE is a natural choice for many students who have no strong preference for a specific industry sector or engineering science specialty, e.g., petroleum, life sciences, pulp and paper, or minerals, because PSE knowledge is applicable to all industries. Also, the PSE skills are applicable in nearly every job category, e.g., design, operations, research, management, and public policy. Second, and perhaps more important, the students gain skills that enable them ***to learn in depth*** by revisiting topics, reinforcing key concepts, encountering advanced technology, learning practical applications, and solving open-ended projects.

2.0 What are the PSE Teaching and Learning Goals?

We define learning goals in Table 2 for PSE in the three categories proposed by Rugarcia[10], i.e., attitudes, skills and knowledge. The attitudes provide the motivation and willingness to address the issues in PSE. To briefly summarize the attitudes, we want our students to recognize that most systems have many degrees of freedom, that opportunity exists to improve performance by adjusting these variables in response to uncertainty, disturbances and changing requirements (e.g., product qualities and production rates). Skills provide the professional and personal abilities to apply engineering knowledge. Students must be able to independently apply problem solving skills to define achievable goals (performance specifications), and they must formulate a structured program to design and implement solutions. Knowledge provides mastery of the unique technical methods in PSE, modeling, automatic control, applied statistics and optimization. Proof of mastery involves applying the appropriate technology in formulating and solving a diverse set of problems, mostly in chemical engineering but selected problems are taken from fields such as business and public policy.

2.1 PSE within the Undergraduate Program

Major topics are presented within the PSE courses, which should be integrated with other aspects of the curriculum. First, we summarize the entire four-year program in Table 3. Basically, the PSE courses begin in the third year, after the majority of basic science and mathematics and a few of the basic chemical engineering have been covered. Naturally, fundamental mathematical modelling is introduced in courses like material and energy balances and heat transfer. A key aspect of our undergraduate program is the accelerated coverage of required chemical engineering courses, so that all required courses except two design courses and one laboratory course are completed by the end of third year. This curriculum provides opportunity for students to build a mature understanding of the chemical engineering core before focussing on the bulk of their technical electives.

Naturally, the core PSE topics are introduced in required courses that are taken by all students, including those in the PSE stream. We recognize that a single course usually does not provide sufficient opportunity to build expertise; therefore, most topics are reinforced with subsequent, elective courses. In addition, students are able to select PSE-related options in two of their fourth-year required courses, covering laboratory experiences and a design project. In total, the PSE stream includes five required courses, two required courses that have PSE-directed options, and three elective courses. The next section describes the allocation of topics to the required and elective courses.

2.2 Division Between Required and Elective PSE Topics

While, we would like all students to master a wide range of PSE topics, we must be realistic about the time the students have for PSE in the core curriculum. Therefore, we have selected required topics that are needed by essentially all practicing engineers and elective topics that are widely applied in practice and enable students to build learning skills.

The topic allocation is presented in Table 4, and a few highlights of the coverage of the required topics are discussed in this paragraph. First, we emphasize that that the topics are not isolated within a specific course. For example, steps for achieving safe design and operation are addressed in both the control and design courses. Second, we note that the major equipment related to PSE, i.e., sensors, final elements, signal transmission, and computing devices, is introduced in the required control course, but it is reinforced in design courses. Third, modelling concepts are covered or reinforced in all PSE courses, because modelling is a basic skill for chemical engineers. We note that students acquire various modelling skills, including fundamental (flowsheeting and design), empirical (monitoring and control) and qualitative (HAZOP and troubleshooting).

The PSE stream involves two sets of courses; (1) elective courses and (2) options within required courses. The specific courses are in Figure 1 and are discussed in the next section. Therefore, only a few introductory comments will be made here. First, the three electives reinforce and extend prior learning in process control and statistics and introduce numerical optimization. Second, the options within required courses provide concentration on a process control laboratory experience and a design experience with substantial dynamics, control and optimization.

Finally, we note that additional electives not in Table 3 are available. For example, students can participate in an individual research project during the last year of undergraduate studies. This course has the weight of a single technical elective, and it can be an excellent learning experience for the student. In addition, courses in other departments can provide greater breadth; currently, the most popular is a course on mechatronics that introduces discrete control using programmable logic controllers (PLC’s).

The offerings will be introduced according to each major knowledge base, as shown schematically in Figure 1; then, aspects that link these knowledge bases will be discussed.

2.3 Overview of the PSE Topics and Courses

The courses will be discussed in three categories: (1) fundamental modelling, simulation, and design, (2) control and operations, (3) experimentation and data analysis.

Modelling, simulation, and design are covered by a sequence of courses that begin with numerical methods and culminate with process design. The first course (3E04) extends fundamental modelling skills and introduces numerical methods; the students perform simulations using MATLAB™. The second course (3G04) introduces flowsheeting using commercial software, as well as introducing process synthesis such a pinch analysis. The third course (4W04) involves a major design project that involves some flowsheeting; PSE students select the design project tailored to the PSE stream objectives and use computational tools appropriate for the project. Typical past PSE projects have included dynamic simulation to investigate the effects of process structure and operating conditions on operability. Finally, an elective course (4G03) is provided to introduce optimization, which covers linear, non-linear, and mixed-integer programming; students learn to model, solve and interpret results using Excel™ and GAMS™. By the completion of these courses, students can formulate models with appropriate fidelity, decide whether to use commercial packages or program solution methods, and use simulations to solve engineering problems.

Control and operations are covered in a sequence of courses that address how both process design and control affect dynamic behaviour. The coverage begins with a required course (3P04) that introduces process control, including dynamic modelling, single-loop algorithms and tuning, enhancements (e.g., cascade and feedforward), and the basics of instrumentation; the course ends by introducing multiloop control. The PSE students select the "control" option for the fourth-year laboratory course (4L02) that involves experiences applying digital control to laboratories on pH and heat exchanger control; the university equipment is controlled using LabView™. The effects of process design on operability are covered in a required course (4N04) in the design sequence. The role of control in safety is introduced using the seven levels of control for safety (AIChE, 1994), which provides coverage of alarms, safety valves and safety interlock systems. This safety material is applied through exercises applying the HAZOP method to process designs. Other topics covered include reliability (e.g., redundancy via parallel equipment and by-passing), flexibility (having adjustable variables to achieve desired conditions) and controllability (being able to move specific dependent variables within an operating region). Finally, an elective course (4E03) covers digital control technology, provides reinforcement for multiloop control design, and provides coverage of Model-Predictive Control[11]. Dynamic simulations and analysis are performed using MATLAB™. By the completion of these courses, the students can design simple multiloop control systems, select equipment that provides safe and reliable systems, and apply the power of digital computation for control and monitoring.

Because engineers deal with data, **experimentation and data analysis** is covered in courses on applied statistics. A required statistics course (3N03) introduces the basics of probability and statistics. An elective course (4C03) covers non-linear regression and experimental design, and it introduces multivariate methods, such a principle components analysis. Students learn how to use data from designed experiments to build causal models for prediction and control, and they learn how to use data from typical plant operation to build correlation models for performance monitoring and fault identification[12]. By the completion of these courses, the students can decide whether causal or correlation models are required, design experiments (as needed), fit models and evaluate the uncertainty of predictions. Exercises are performed using Minitab™.

2.4 Integration of Topics in PSE Courses

The PSE courses introduce progressively more complex methods as students proceed through each of the major categories of integrated topics. Naturally, the capstone design course (4W04) provides an excellent opportunity to integrate all previous courses. To improve student learning, key concepts are reinforced and viewed from different perspectives throughout the last two years. These are essential "cross links" that enable students to recognize the integration of skills and knowledge in PSE. A few examples of cross links are given in the following.

- **Fundamental Modeling** - The key challenge is to develop a model of appropriate fidelity for the specific engineering application, i.e., one that supports the design, operations or control decision. For example, students deal with very complex, fundamental models in flowsheeting, while they employ approximate, linearized models in process control. Even though these courses occur during the same semester, the likelihood is high that students will not recognize the reasons behind the modeling choices. Therefore, the instructors explain the differences in models based on the application, (1) detailed non-linear models for investigating major changes in system structure and variable values and (2) linear, approximate models for small changes in variable values associated with control design and controller tuning.

- **Empirical modeling** - The importance of causal empirical models is emphasized in the control, statistics and optimization courses. The control courses discuss issues related to experimenting in a real plant and methods for comparing empirical models with expectations from fundamental analysis. The advanced statistics course introduces experimental design for model building and process improvement.

  The statistics course also contrasts causal models with correlation models that are based on typical plant data without designed perturbations. Important applications of correlation models are explained for inferring unmeasured variables and identifying faults. Building these models often requires the application of multivariate statistical methods to prevent "overfitting" of the data. The application of multivariate statistics (principle component analysis, PCA, and partial least squares, PLS) is an important distinction of our program and demonstrates the level of advanced technology that can be made accessible to undergraduates in technical electives.

- **Numerical methods and simulation** - Engineers determine the steady-state and dynamic behaviours of complex systems by simulation. Therefore, they must master the basic numerical methods for solving models, and they must be able to design simulation cases that inform design and operations decisions. Numerical methods are introduced in a modeling course (3E04) and are reinforced and extended in many subsequent courses, e.g., Process Control (3P04 and 4E03), Flowsheeting (3G04) and Optimization (4G03). These courses place emphasis on the interpretation of results, as well as model formulation and solution.

- **Dealing with uncertainty** - Uncertainty is considered throughout the program, with the basic concepts introduced in the required statistics course (3N03). It is revisited in the control courses (3P04 and 4E03) with applications in sensor accuracy and in robust controller tuning for an uncertain plant. The effects of uncertain physical property data are investigated in the flowsheeting course (3G04). In addition, uncertainty in process conditions is considered when designing equipment with capacities adequate for a range of operations conditions. Finally, uncertainty is the motivating reason to apply well-established sensitivity analysis in optimization (4G03).

  Naturally, the advanced statistics course (4C03) deals extensively with this topic. For example, statistical process control demonstrates the difference between common cause and special cause variability, which justifies the Statistical Process Control (SPC) strategies that respond to only variability that is deemed to be special cause.

- **Design and Operations** – PSE provides the knowledge for modelling complex process networks using a flowsheeting package, e.g., Hysis™. In addition, they learn approaches for process synthesis in separation trains and heat exchanger networks (using HX-NET™). Students solidify their mastery of these tools by performing open-ended exercises involving structures and material and energy balances of plant sections.

  Far more engineers are involved in operations than design because, "We build a plant once, but we operate it every day for 30 years." As a result, design must be performed with an eye to good operability. Here, we use the term "operability" to designate a range of objectives including

  1. **equipment capacity** for a range of production rates, products, feed materials, disturbances and other factors that define an operating window
  2. **flexibility** to achieve desired conditions within the operating window, which can require by-passing, extra utility flows, and excess capacity
  3. **reliability** that requires parallel equipment, storage vessels, by-passing for maintenance without shutdown, etc.
  4. **safety** following the levels of safety proposed by the AIChE[13] and evaluated using HAZOP[14]
  5. **efficiency** that increases operating profit
  6. **operation** during transitions, including batch, startup/shutdown, and regeneration
  7. **dynamic behaviour** including good control performance
  8. **monitoring and diagnosis**, including sensor selection for troubleshooting and longer-term process performance monitoring

  The PSE courses introduce these topics, explain their importance for process operation, and emphasize that excellence is achieved only when these factors are explicitly considered when the process is designed. By introducing the perspective of "operability", PSE extends the design perspective from a single point to a (potentially large) region of operation. See Marlin[15] for proposals for teaching and learning operability.

- **Process Monitoring** - All processes are monitored for safety, equipment performance, product quality, efficiency and other key performance indices (KPI's). Education in this area is important because it is an important aspect of engineering practice and because it is a nice way to reinforce principles. Our program prepares students to monitor using fundamental concepts for quantitative analysis (e.g., energy/kg of product) and qualitative trouble shooting (e.g. fishbone diagrams). In addition, we prepare students to use statistical methods for fault diagnosis that utilize all available sensors. Based on these learning experiences, students appreciate the importance of designing plants with adequate sensors for monitoring, as well as for feedback control.

Naturally, students apply all of their knowledge and skills in the final-semester design project. The PSE-related design project includes an investigation of process structure and dynamics on the efficiency and operability of the process.

2.5 Industrial Case Studies and Experiences

Realistic industrial cases and hands-on industrial experiences are included in the PSE stream. An industrial case study is introduced in the flowsheeting course, where students perform a major design project on a section of the plant. Since the students have learned about the process chemistry and flowsheeting of this process, the same plant is used in subsequent PSE courses in workshops covering instrumentation, process control, troubleshooting, safety and HAZOPS in both control and design courses. Currently, the case study involves a maleic anhydride plant. This plant is located near the university, and students have the opportunity to visit it.

Hands-on industrial experiences are provided in the process control laboratory, when students perform a laboratory in the facilities of Xerox Research Centre of Canada, which is commuting distance from the university.

Substantial additional experience is gained through a project in the university boiler house. Students study a process unit (e.g., condensate return and boiler water treating) , evaluate its design and operability, perform a HAZOP analysis, summarize trouble shooting, perform an estimate for capital and operating costs, evaluate a process modification for technical feasibility and economic attractiveness. This project also introduces safety in an operating plant, and provides students the opportunity to work with plant operations personnel.

Finally, we invite industrial practitioners to give guest lectures that give students the opportunity to hear different views on technical topics and learn about expectations from practicing engineers.

2.6 Learning Outcomes

McMaster University is located in Canada and participates in the Canadian Engineering Accreditation Board reviews (CEAB[16]); we do not participate in the ABET accreditation system (ABET[17]). Therefore, we do not perform a formal evaluation of learning outcomes using the ABET categories a-k. However, we have prepared a summary in Appendix A giving our views of how the PSE program contributes to the key ABET learning goals.

3.0 Teaching and Learning Methods

PSE material is presented using a range of teaching and learning methods that reflect the needs of the courses and the preferences of the instructors. Since the material is concentrated in the last two years of the undergraduate program, many courses include projects that integrate the prior knowledge with PSE technology. Some of the instructors use Problem-based learning to involve students in problem definition and open-ended problem solving[7].

In addition, two of the courses are “home” for instruction in professional skills such as learning preferences, self-directed learning, group skills, meeting and chairperson skills, and trouble-shooting. While the PSE courses provide a wide range of problems to practice these skills, we believe that the instructor’s interests and enthusiasm for these topics in more important than the specific technical topic of the course in which professional skills are introduced. Naturally, all courses should offer students the opportunity to practice these professional skills.

4.0 Experiences with the PSE Stream

We have offered several courses in PSE for many decades, and we have presented the formal PSE stream since 2002. This discussion will summarize experiences of the students, faculty and industry.

4.1 Student Experience

- **Popularity of the courses** - The students “vote with their feet” by attending the PSE electives in large numbers. Each course is attended by over 50% of the eligible fourth-year students, and the advanced statistics course has the highest enrolment, nearly 90% of the eligible students!
- **Integrated PSE courses** - The PSE stream integrates required and elective courses. In some cases, options within the required courses enable students to focus on PSE topics while obtaining a rounded engineering education and satisfying accreditation requirements.
- **Four-year program** - The stream can be completed within the four-year program, which enables students of experience learning in depth without extending their undergraduate studies. Students seeking further expertise want to enter a graduate program.
- **PSE Completion rate** - Ten students out of the 2006 graduating class of 60 students completed the PSE stream requirements and applied for the official designation on their transcripts. At first, this seems like a low number, given the attendance of at least 30 students for every PSE course, including electives. However, we observe that many

students complete nearly all of the PSE requirements, but miss one or two courses so that they can take an elective that interests them. This was initially surprising to the faculty; however, we feel that all students benefit from the systems approach and can fill in any gaps later during their professional careers.

- **Preparation for further studies** - Students completing the stream are well prepared to continue in graduate studies. They have applied the systems approach not only to PSE technical graduate programs, but also associated fields like MBA with concentration in operations research and public policy with emphasis on systems analysis.

We note that this positive experience contradicts some "accepted wisdom" about PSE. For example, we have seen several universities reduce the PSE content in the core curriculum, including offering process control as an elective (only) and having little or no statistics. Our experience indicates that undergraduate students will embrace a systems program and approach when provided with the coherent explanation of its role in chemical engineering and provided that the courses provide an opportunity for excellent learning experiences. We are happy to report, "If you built it (well), they will come!"

4.2 Faculty Experience

From the faculty side, we have been offering PSE-related technical electives for over twenty years. In addition, we have a strong research presence in Process Systems Engineering and extensive industrial interactions at the graduate level[18]. Therefore, we have the staff, experience and expertise to offer the stream, including during periods when one of the course instructors is on sabbatical. Also, since we have a substantial research activity, a number of qualified teaching assistants are available for these courses. Finally, we enjoy teaching these courses, since we can add our experiences and insights to the teaching materials available.

4.3 Employer interest

We continue to receive job postings from companies seeking graduates with strong PSE skills. Several companies will consider our undergraduates for positions requiring a Masters degree. Recently, companies have approached us to build a stronger co-op relationship, since they want to have a good chance of hiring our students from the PSE stream.

5.0 Opportunities for Enhancements

We believe that we offer a unique and valuable educational experience for our undergraduate students. However, nothing is perfect, and we recognize that the current PSE stream does not yet offer students every opportunity that we would like. Some of the key enhancement opportunities are discussed briefly in the following.

- **Instrumentation** - Studying sensors provides important insights into the capabilities and limitations (accuracy, reproducibility, reliability, etc.) of real-time measurements that are critical for systems engineering. We currently cover this large topic in the introductory process control course. However, we are planning to modify a required analytical chemistry course to include basic sensors (flow, pressure, temperature, level), along with a selection of chemical analyzers and sample systems. This course will be required for all chemical engineering students.

- **Computer programming** - Surveys indicate that many companies expect students to have moderate programming skills[19]. Currently, our courses emphasis model structures and solutions using packages, e.g., MATLAB™, GAMS™, HYSIS™, etc. We continue to seek opportunities for our students to take a course covering program design and several languages (e.g., C++ and Visual Basic).
- **Dynamic flowsheeting** - While we encourage students to use commercial PSE software products, we believe that the current products for *dynamic* flowsheeting are not yet appropriate for undergraduate education. One major issue is the lack of a library containing a wide selection of process models, for example, fired heaters, boilers, compressors, evaporators, various heat exchangers and so forth. The second major issue is the burden placed on the students to learn extensive product-specific knowledge. We continue to seek a dynamic modelling system that enables students to learn and apply PSE technology, since dynamic simulations provide excellent feedback on their proposed designs. Note that we use menu-driven programs in MATLAB for students to investigate the dynamics and control of process systems, which are non-linear, have noisy measurements, and have a few controlled and manipulated variables, e.g., a distillation tower or fired heater. These tools are valuable, but they do not address learning goals associated with complex process structures, including allowing students to modify the structures.
- **Graduate Studies in Engineering Practice** - Our university offers selected programs for a Masters Degree in Engineering Practice that complement our research-oriented graduate programs (MSEP[20]). A new applied Masters of Engineering Design in Process Systems Design and Operability will accept its first students in the fall of 2007 (CED[21]). We expect that this program will have synergies with the undergraduate stream, to the benefit of both in teaching and learning materials and industrial case studies.

6.0 Conclusions

We have developed an undergraduate program that includes required and elective topics in Process Systems Engineering (PSE). The topics are presented in an integrated manner throughout many courses. The PSE stream builds on the required courses to offer students the opportunity to follow their interests, build on prior learning, learn about industrial practice, and engage in numerous open-ended projects. The graduates are well prepared for industrial careers or graduate studies.

The PSE stream has been very well received by students, as measured by consistent high enrolment in the course offerings. We attribute this to the applicability of the PSE topics to a wide range of applications in engineering, business and public policy. This enables students to build expertise without selecting a specific engineering application. We continue to consider actions to improve the stream; for example, we will be instituting a new course to enhance the coverage of measurement systems.

We believe that our experiences can be useful to several groups. First, our choices of PSE topics for required and elective courses can be used as a reference by departments in designing their programs, specifically the required PSE material. Second, departments considering streams can use the ideas here, for example, the use of course options to strengthen a stream, when designing streams in other technical areas. Finally, a few departments will be considering a strong undergraduate program in PSE, and the program that we have implemented can serve as a guide for their decisions.

References

1. Edgar, T., Ogunnaike, B., Downs, J., Muske, K., and Bequette, B.W. (2006) Renovating the Undergraduate Process Control Course, *Comp. Chem. Eng*., 30, 1749-1762.
2. Grossmann, I.E., and A.W. Westerberg (2000). "Research Challenges in Process Systems Engineering," Invited Perspective, AIChE J, 46(9), 1700-1703
3. Perkins, J., (2002) Education in Process Systems Engineering: Past, Present and Future, *Comp. Chem. Engr*, 26, 283-293
4. Felder, R. (2007) Resources in Science and Engineering Education, http://www.ncsu.edu/felder-public/ last visited February 7, 2007.
5. Fogler, H. Scott and Steve LeBlanc (1995) *Strategies for Creative Problem Solving*, Prentice Hall PTR, Upper Saddle River
6. Wankat, P. (2007) Teaching Engineering, https://engineering.purdue.edu/ChE/News_and_Events/ Publications/ teaching_engineering/index.html, last visited February 7, 2007.
7. Woods, D. (1994). *Problem-Based Learning: How to Gain the Most from PBL*, D.R. Woods, Waterdown, Ontario.
8. Armstrong, R. (2006). (http://mit.edu/che-curriculum/index.html) last visited February 7, 2007.
9. Pritchard, C. (2003) Make It a Double, *PRISM*, 12 (8), 37-38 , April 2003
10. Rugarcia, A., R. Felder, D. Woods, and J. Stice (2000). The Future of Engineering Education, *Chem. Engr. Ed*., 34, 16.
11. Qin, S. J. and T. Badgwell (2003) A Survey of Industrial Model Predictive Control Technology, *Contr. Eng. Practice,* 11, 733-764
12. MacGregor, J.F., H. Yu, S. Garcia-Munoz and J. Flores-Cerrillo, "Data-base Latent Variable Methods for Process Analysis, Monitoring and Control", Computers & Chem. Eng., 29, 1217-1223, 2005.
13. AIChE, (1994) *Guidelines for Safe Automation of Chemical Processes*, American Institute of Chemical Engineers, Research Triangle Park, NC
14. Kletz, T. (1986). *HAZOP and HAZAN, Second Edition*, The Institute of Chemical Engineers, Warwickschire, UK.
15. Marlin, T. A (2007) Teaching "Operability" in Undergraduate Chemical Engineering Design Education, ASEE Annual Conference, Honolulu, Hawaii, June 24-27
16. CEAB (2007) http://www.ccpe.ca/e/ccpe_boards_2.cfm last visited February 7, 2007.
17. ABET (2007) http://www.abet.org last visited February 7, 2007.
18. MACC (2007) http://www.macc.mcmaster.ca/ last visited February 7, 2007.
19. Edgar (2007), http://www.cache.org/Edgar-computing%20through.html (See Appendix A) last visited February 7, 2007.
20. MSEP (2007) http://msep.mcmaster.ca/ last visited February 7, 2007.
21. CED (2007) http://msep.mcmaster.ca/ced_process.html last visited February 7, 2007.

Table 1. Ranking of technical knowledge by industrial practitioners
(Data from Edgar[1])

Knowledge	Ranking on scale of 1-10 (10 = most important)
Optimization of a process or operation	8.6
Statistical analysis of data and design of experiments	7.2
Physical dynamic process models	7.0
Statistical/empirical dynamic process models	6.9
Multivariable interactions and multivariable system analysis	6.6
Statistical process control and process monitoring	5.3
Design and tuning of PID loops	5.1
Nonlinear dynamics and analysis of nonlinear systems	3.9
Frequency domain analysis	2.4
Expert systems and artificial intelligence	1.9

Table 2. Teaching and Learning Goals for Process Systems Engineering (PSE)

Attitudes

We build systems that are flexible and contain features that enable it to adapt to changing conditions and objectives.

We make decisions with imperfect (uncertain) information. We can apply technology to reduce uncertainty and to make the best decisions for uncertain systems.

We base all PSE analysis on deep knowledge of engineering science and process equipment.

Skills

We proceed from specifications to engineering products. As engineers we know how to set specifications and work toward cost-effective designs that satisfy multiple criteria, e.g., safety, product quality, production rate, profit, and monitoring and diagnosis.

We can independently investigate and report on topics beyond our current knowledge.

Knowledge

We know how to formulate an appropriate model for the problem at hand. The model could be based on fundamentals, empirical data, or a combination of both.

We can apply technical knowledge in modelling, process control, applied statistics, and optimization to engineering problems.

We understand fundamentals of measurement, error analysis, and instrumentation (sensors and final elements).

We can solve PSE problems using computer tools, e.g., spreadsheeting, flowsheeting, data analysis, and programming, e.g. MATLAB.

Table 3. Distribution of credit hours for a student in the Process Systems Engineering (PSE) Stream

	Year 1	Year 2	Year 3	Year 4	Sub-total
Basic science and math	21	12	9	0	42
Professional skills	3	3	*	*	6*
Complementary studies	6	6	0	6	18
Engineering science	7	12	17	12	48
PSE	**0**	**3**	**12**	**19**	**34**
Sub-total	37	36	38	37	148

* Professional skills are explicitly included in two PSE courses, and report writing is required in at least six courses in the third and fourth years.

Table 4. Allocation of PSE Topics to Required and Elective Courses.

Topic	Addressed in Required Courses	Addressed in PSE Course Options and Elective Courses
Steady-state Modelling	• Formulate models • Solve numerically • Use commercial flowsheet software • Select appropriate physical property packages	• See Optimization below
Dynamic Modelling	• Formulate models • Solve analytically and numerically • Relate behaviour to physical system (e.g. time constant and gain) • Perform and interpret process reaction curve experiment	• Use commercial dynamic flowsheeting software • See statistics below
Design	• Process synthesis, e.g., pinch technology • Safety (e.g., safety hierarchy and HAZOP) • Operability (feasible region, flexibility, reliability, etc.) • Process troubleshooting • Complete major project from definition to equipment specification	• Effect of process structure, e.g., recycle, on dynamic behaviour • Control system design • Optimization of design
Process Control	• Concepts of dynamic stability and feedback • Effects of process dynamics on feedback performance • Cascade and feedforward • Simple multiloop control • Basic instrumentation	• The effects of interaction, e.g., relative gain analysis • Digital implementation • Model Predictive Control • Control design using multiloop technology • Extensive laboratory experience
Applied statistics	• Basic Probability • Hypothesis tests • Linear regression • Applications in laboratory courses	• Statistical process control (SPC) • Experimental design, including optima designs • Non-linear regression • Introduction to multivariate statistics (e.g., Principle components analysis) • Use commercial software
Optimization	• Applications of basic calculus • Plot objective versus one or two degrees of freedom	• Identify opportunities (tradeoffs) • Formulate models: objective function, equalities, inequalities, and variable bounds • Linear programming, MILP, and non-linear programming • Use standard software packages

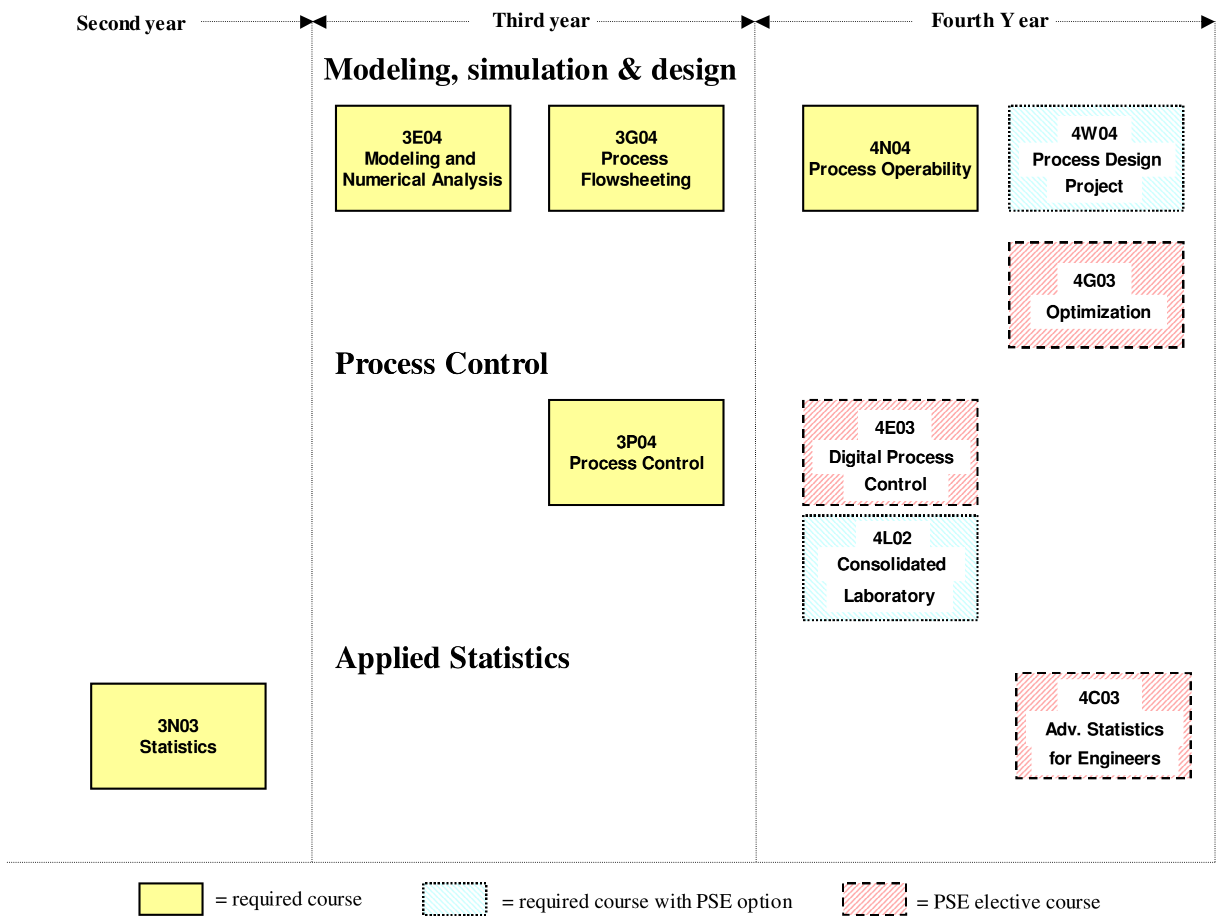

Figure 1. Overview of PSE courses.

Appendix A. Summary of PSE's contribution to achieving ABET outcomes.

	ABET Category	PSE Stream
a.	an ability to apply knowledge of mathematics, science, and engineering	PSE emphasizes a model-centric view of engineering that enables students to formulate models based on fundamentals of physiochemical systems and/or appropriately designed experiments. The use of these models for decision support is a central aspect of PSE.
b.	an ability to design and conduct experiments, as well as to analyze and interpret data	Our view of PSE places applied statistics in the core of PSE technology. The design of experiments for modelling goals is covered extensively, including applications in control and process development. In addition, building and using empirical models derived from "typical" operating conditions, without experimental intervention, is addressed with applications of multivariate statistics for soft sensors and fault detection.
c.	an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	Students establish objectives as a first step in the design of control and process systems. The objectives and the subsequent engineering products explicitly include economics, environment, health and safety (including that of personnel in plants and consumers of products), and manufacturability (operability). The quantitative integration of constraints in decision making is addressed in optimization. Social, political issues are not addressed in our PSE program. Sustainability is addressed in the limited role of maintaining process operations, but does not address the global issues around raw materials, environment or waste processing.
d.	an ability to function on multi-disciplinary teams	Numerous team experiences are provided, including guidance on developing group norms, chairing meetings, developing agendas and writing summaries (management digests). Our program does not include experiences with multi-disciplinary teams, i.e., with non-engineering students.
e.	an ability to identify, formulate, and solve engineering problems	The program includes instruction on problem solving and experiences in applying the six-step method in engineering practice, including trouble shooting. In some instances, the students are required to define the subject of their project, e.g., a process for which they study operability issues.

f.	an understanding of professional and ethical responsibility	Students integrate safety as one of the (competing) multiple objectives in their designs and operating policies for complex systems. The rights and responsibilities of all workers are introduced as part of safety training before visiting industrial facilities. Ethics is addressed peripherally in the PSE courses and explicitly in a separate course.
g.	an ability to communicate effectively	The courses offer guidance on writing and oral presentation. At least four course projects involve written reports and three require presentations; these communication experiences are in addition to laboratory reports. Emphasis is placed on interpreting and communicating the results of modeling and optimization studies.
h.	the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	The PSE program provides techniques for studying the behaviour of integrated systems. Some students perform projects addressing public policy, e.g., multi-criteria optimization for power generation in a province. The broader social context is addressed in PSE courses during discussions, but it is addressed formally in other complementary studies courses.
i.	a recognition of the need for, and an ability to engage in life-long learning	PSE courses introduce skills for life-long learning and engage students in exercises in which they participate in the defining learning goals, teaching themselves and designing evaluation instruments, i.e., self-tests. Several courses include projects that require students to research topics that are not included in course resources provided by the instructor.
j.	a knowledge of contemporary issues	Contemporary societal issues are not explicitly addressed
k.	an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice	The PSE courses are maintained current by instructors who are engaged in graduate research and consulting in engineering practice. Students use state-of-the-art commercial software, and recent developments in the field are introduced in the advanced (elective) courses. Numerous industrial experiences reinforce the importance of a high level of technical expertise.