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Teaching of Process Design Courses – The CMU experience, trends and challenges

Ana I. Torres and Ignacio E. Grossmann*

Department of Chemical Engineering, Carnegie Mellon University, Pittsburgh, PA, USA
* Corresponding Author: grossmann@cmu.edu

ABSTRACT

Carnegie Mellon University (CMU) has a strong tradition and expertise in Chemical Process Systems Engineering. This short article comments on the CMU PSE-related courses and describes in more detail our approach to teaching Chemical Process Design. We discuss (i) our emphasis on proposing processes related to energy and sustainability and (ii) some of the challenges that are currently faced when teaching this course.

Keywords: Process Design, Education

INTRODUCTION

Process design has been the traditional capstone course for chemical engineering. It is generally the course where the material learned in previous semesters is integrated and applied to a major design project. A major component of this course is decision-making since students have to select the process technology, the flowsheet configuration, and its operating parameters. Modern educational trends emphasize process invention [1] (i.e., synthesis of flowsheets) and the teaching of systematic techniques for design. These include synthesis strategies (e.g., hierarchical decomposition, separation synthesis, heat exchanger networks, energy integration, and water networks), process simulation tools to perform the mass and energy balances, detailed modeling tools for chemical reactors and separators, and economic evaluation.

Process design projects are also ideal for introducing emerging topics such as energy, decarbonization, and sustainability and environmental justice which are becoming highly relevant in the professional education of chemical engineering students. In our experience, students have been highly motivated by design projects that focus on these areas, which in turn can help increase enrollments in chemical engineering.

In this paper, we provide an overview of the Process Systems Engineering related courses offered at CMU and describe, in detail, our approach to teaching Process Design.

PROCESS SYSTEMS ENGINEERING COURSES TAUGHT AT CMU

Dating back to the pioneering vision by Professor Arthur Westerberg in the late 70s, Process Systems Engineering (PSE) is a major research and education strength of the Chemical Engineering Program at Carnegie Mellon University. Currently, five tenure track faculty members (Biegler, Gounaris, Grossmann, Laird, Torres) focus their research on PSE. They maintain an active research environment, seminar series, the CAPD industrial consortium [2], and a cohort of graduate students at the master's and doctorate levels. The CAPD faculty have written several textbooks in the area [3-7] .

While many chemical engineering programs struggle to cover design courses with tenure-track faculty [8] within a curriculum, our strength in this area of Chemical Engineering allows us to cover design-related courses with specialists. This tenure-track faculty is complemented by adjunct faculty with extensive industrial experience who actively participate in teaching design courses covering practical topics such as process safety.

At CMU, the Chemical Process Systems Design course is the major engineering design experience required by ABET [9]. This course represents 12 units, where one unit expects one hour per week of work and is taught during the fall semester of the senior year (fourth year). Then, students take Chemical Product Design (9 units) in the spring semester of their senior year. These courses build on previous courses that include two design-related courses: Unit Operations (9 units) in the junior year and Unit Operations Laboratory (9 units) in the senior year, and two PSE-related mini-courses (6 units each): Numerical Methods and Machine Learning for Chemical Engineering and Optimization Modeling and Algorithms taken during the fall semester of the junior year. The PSE sequence is completed by Chemical Engineering Process Control (9 units) taken in the senior spring semester.

At the graduate level, we regularly offer three PSE-related courses: Advanced Process Systems Engineering (A-PSE), Process Systems Modeling/Design and Optimization of Sustainable Processes (PSM), and Computational Methods for Large Scale Process Design & Analysis (CMPMO).

A-PSE covers the fundamentals and algorithms of optimization techniques for linear and nonlinear programming, mixed-integer linear and nonlinear programming, generalized disjunctive programming, flexibility analysis, and stochastic programming. It also covers the application of these techniques to the synthesis of heat exchanger networks, distillation sequences, water networks, and process flowsheets as well as the planning and scheduling of batch and continuous processes.

PSM is a long-standing course targeted at masters-level students that covers the simulation and optimization of complex flowsheets using Process Simulation Software. Starting in 2025, this course has been reformulated to (i) introduce these topics in the context of sustainable process design and (ii) improve the process de-sign, simulation, and evaluation skills for those graduate students who come to the PhD program without a strong Process Design background. PSM currently covers modeling simulation evaluation and optimization of state-of-the-art technologies for the conversion of biomass and waste to fuels and chemicals, electrification of chemical processes, the use and storage of energy from intermit-tent non-programmable sources (including batteries, hydrogen, and chemicals), and carbon capture, among others. The course is also offered as an elective for under-graduate senior and PhD students. Currently, all students have the same assignments regardless of whether they did the full PSE sequence at CMU or not.

CMPMO deals with the underlying computer-aided design techniques for steady-state and dynamic simulation, numerical solution and decomposition strategies for large systems of sparse nonlinear algebraic equations, stiff ordinary differential equations, strategies

for mixed algebraic/differential systems and computer architectures for process systems.

In addition, more specialized courses are offered in an intermittent fashion as Special Topics courses: Nonlinear Optimization in Process Systems Engineering is aimed at graduate-level students and is based on the textbook in [4]. It covers methods for solution and optimization for engineering systems described by nonlinear algebraic and/or differential equations. Production and Supply Chain Optimization also targets graduate students and aims to familiarize them with popular decision-making contexts related to production and supply chain optimization and with the numerical optimization methods (both model-based and metaheuristics-based) employed in such settings.

OUR APPROACH TO TEACH CHEMICAL PROCESS SYSTEMS DESIGN

As with many capstone design courses, Chemical Process Systems Design covers screening process alternatives and computational strategies for preliminary material and heat balances in large chemical processes, including preliminary sizing of process equipment. A key part of the course is evaluating the economics of alternative flowsheet configurations and technologies. Currently, the teaching team comprises two tenure-track faculty, one adjunct faculty, and four teaching assistants (TAs), who are usually PhD students. Class size has oscillated over time and is currently at 50-60 students per cohort.

The course involves lectures and a major project. The main topics in the lectures include techniques for the conceptual design of chemical processes, preliminary process calculations, systematic methods for pro-cess synthesis and energy recovery, economic evaluations of competing processes, fundamentals of flowsheet simulation, and design and scheduling for batch pro-cessing. These topics are covered in the textbook that is used in this course, "Systematic Methods of Chemical Process Design" [3]. Students are also given as references the textbooks by Seider at al [11], Towler and Sinnot [12] and Turton et.al [13]. Students are given two tests that are graded: the first on preliminary mass and energy balances and equipment sizing to prepare them for memo 2; the second on economic evaluation and pro-cess synthesis to prepare them for their final report, project memo 3.

The project itself, for more than a decade, has been defined with input from Dr. Jeff Siirola an expert in process design, former Technology Fellow at Eastman Chemical Company, and current Professor of Engineering Practice at Purdue and Adjunct Faculty at Carnegie Mellon University. The project is organized around the design of a process for a hypothetical "Andrew Corporation" that requests their team of engineers within the Special Projects Group to study a novel processing approach. For example, the 2022 course dealt with the design of a blue hydrogen plant, the 2023 course with chemical depolymerization of PET plastics, and the 2024 course with polyolefin depolymerization.

Students are required to work in a self-selected team of four people. All teams are given the same memo with a brief description of the project, design specifications, and constraints such as production rate, product purity, available feedstocks, location, and economic data. It is important to note that the project is a new unsolved problem, so each team must conduct a literature review and gather data on relevant technologies and chemistries, process conditions, etc., to come up with their own solution. After the preliminary literature review, each team is expected to postulate a superstructure with the major alternatives they have found and, from it, extract a process flowsheet with all the major pieces of equipment and approximate operating conditions.

Students are asked to solve the mass and energy balances for that flowsheet by considering simplified (linear) models for the unit operations prior to using commercial process simulators. Formulating these equations and solving them using simple spreadsheets serves the purpose of teaching the students approximation techniques to allow them to quickly screen design alternatives by generating reasonable first guesses. These first guesses help in building intuition and greatly simplify subsequent rigorous modeling in commercial simulators. We use Aspen Plus as the process simulation software. At CMU, Aspen Plus is also taught as part of the Design Course; this is, students do not generally have prior expo-sure to the software.

In addition, students must perform heat integration using pinch analysis and perform an economic evaluation to determine the net present value or breakeven point of their proposed design. We use and teach commercial software (Synheat, Aspen Energy Analyzer, As-pen Process Economic Analyzer) to facilitate calculations. Safety analysis is covered via a Failure Modes and Effects Analysis (FMEA). Starting in 2024, students are also required to perform a gate-to-gate emission evaluation. To this end, we use EPA's GREENSCOPE tool [10], whose use and logics is also introduced during lectures.

To mock a real engineering position, each team is assigned a TA or faculty member who acts as the project manager to whom the students report progress on a weekly basis. The TA/ faculty member also provides guidance to the students on establishing appropriate goals and planning doable tasks to meet the project objectives. It is worth noting that teams create their flowsheets/designs throughout the course and do not share them with other groups. Hence, their proposed flowsheets differ despite addressing the same design project.

We evaluate the designs by requesting students to submit three reports in the form of memos. The literature search and flowsheet development are reported in Memo 1, preliminary mass and energy balances in Memo 2, and full economic evaluation, gate-to-gate environ-mental assessment, and FMEA analysis in Memo 3. Finally, students give a final oral presentation to summarize their major findings in the design project, which is judged by the TAs, faculty members, and people from industry. We invite industrial colleagues (usually members of the CAPD center) to attend these final presentations. Students are given 5 minutes for the presentation with 5 minutes for questions. The short 5-min presentations force the students to highlight their major results, findings, and recommendations to an industrial audience. The fact that real engineers judge their designs and presentations greatly motivates the students and adds reality to the design experience. The evaluation of the course itself is completed by weekly short homework exercises that assess what was covered in the week and two midterm exams that assess the students' performance at the individual level.

THE GOOD, THE BAD AND THE CHALLENGES

From the activities described above, the CMU Process Systems Design experience is clearly a challenging one. Feedback from the students indicates that they tend to spend more than the 12-hour expectation, typically 17 hours on average. A number of factors may influence this perception, some of which are discussed below. Despite the time commitment, students find this course to be one of the most valuable ones. As examples, the following sentences are copied verbatim from the 2023 and 2024 faculty and course evaluations (FCEs):

> "I personally thought that while Memo was a ton of work and involved an overwhelming time commitment, it was definitely one of the most useful assignments Ive done in the ChemE curriculum so far in actually preparing us for the future. "

> "While this class was a ton of work I really learned a lot (...) The material is important to a career in chemical engineering, and the skills feel transferable."

> "This course was a lot of work, but I am happy with what I learned from it. It was clear to see the importance and relevance of the coursework with content even from intro tied in. Thank you."

Personal interaction with the students indicates that focusing the project on current topics of relevance, such as clean energy, decarbonization, and sustainability, is, in general, very well received. The positive reception seems to be linked to two facts. One is that these topics are becoming highly relevant in the Chemical Engineering job postings, and being knowledgeable of the newer technologies differentiates them from other applicants. The second one is that designing novel processes adds the innovation edge that is common in the final projects of other engineering disciplines; this innovation edge is missed if we pick known designs of commodity chemicals as the case study. The downside of selecting novel processes is that some of the operations required to model and simulate them are not well covered in Chemical Engineering curricula, not only at CMU, but to the best of our knowledge across the USA. In addition, commercial simulators do not really have advanced models for non-traditional components such as different types of biomasses. As an example, the polymer recycling processes considered in the last two years required solid processing operations which students were not familiar with; verbatim comments from the FCEs are as follows:

> "Handling of Solids for the project is really problematic when important solid separators are not taught in class."

> "... solids modeling is so difficult in ASPEN and very little was done analytically. "

As faculty, we may argue or expect senior students to be able to learn about novel operations from literature independently. However, for reasons that are not clear to us, self-learning is a barrier for our students.

Another major challenge we face when teaching the process design course is the increasing reduction of fundamental chemical engineering courses (e.g. thermodynamics, fluid mechanics, heat and mass transfer, unit operations) at the expense of the introduction of new courses. Some of these courses are related to new chemical engineering areas (e.g. biological engineering and nanomaterials) and some to general education requirements. These new courses certainly enrich students' education; however, this decrease in fundamentals impacts the design course teaching as one must cover additional basic topics that would have been taken for granted 10-15 years ago. At this point, we as instructors phase the dilemma of cutting process design material, thus lowering the educational value of the course, or phase increasingly lower FCEs as our course is perceived as being too demanding. The latter not only lowers the morale of faculty but also affects faculty's careers as in most American universities, FCEs are one of the main metrics taken into account for faculty reappointment and promotion. In our view, this trend of decrease in fundamentals could be reversed by assigning more hours per week to the design course, e.g., in our case at CMU, for example from 12 to 15 hours. This has been our de facto approach.

From our perspective, the trend in lower process design skills seems to be happening across many ChemE programs. This comment is supported by the authors' observation of our graduate student cohort, including those who come to CMU to pursue MS and PhDs in the PSE at the graduate level. Most of these students have excellent analytical skills and are very well-trained in programming. Many of them are also familiar with the use of commercial process simulators. However, a worrisome problem is that, more commonly than not, students are unable to distinguish between conceptual design and plant design or have the intuition to critically assess whether the result of a simulation makes sense or not. In terms of process evaluation, most students have been exposed to cost correlations to estimate equipment purchase costs. Still, not too many know how to go from equipment purchase cost to installed equipment cost or which terms should be included in operating expenses. We hypothesize that this might be the result of the shift from tenure to non-tenure track faculty reported in [8]. It is only those departments that have faculty in process systems engineering that a regular faculty member teaches the design course. We believe this is a worrying trend because it means that the faculty will increasingly become unable to teach this core course in undergraduate chemical engineering. We very much hope that this trend will be reversed in the future.

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